RESEARCH STUDY FOR DEVELOPMENT OF TECHNIQUES FOR JOINING OF DISSIMILAR METALS

by

C. H. Crane

D. T. Lovell

W. A. Baginski

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ABSTRACT

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A research program was conducted to:

1. Study and investigate potential methods for joining 2219 aluminum alloy to 321 stainless steel.

2. Demonstrate, on a laboratory scale, the feasibility of adapting the most promising method to production requirements.

Joining methods were sought which had the potential capability of producing large diameter (20 to 50-inch) cylindrical assemblies with resulting structural integrity for a service temperature range of 77°F to -423°F.

State-of-the-art cognizance was established by a comprehensive literature survey and analysis of present technology. The survey and analysis indicated that no presently developed method readily satisfied the joining requirements. Therefore, the three most promising methods - diffusion bonding, brazing and fusion welding - were selected for further study and development in this program.

This evaluation proved diffusion bonding to be the best method for joining 2219 aluminum alloy to 321 stainless steel. The unique bonding method developed herein produced high strength, ductile joints and utilized diffusion aids as well as low processing temperatures and short bonding times to effectively control formation of embrittling phases at the joint interface. By comparison, the fusion welding and brazing methods inherently resulted in formation of embrittling phases at the interface. As a result of this and other difficulties associated with processing, the fusion welding and brazing methods were shown to be less desirable than the diffusion bonding method for large component joining.

Successful diffusion bonding was accomplished at (1) temperatures of 500°F to 600°F, (2) pressures of 20 to 25 ksi and (3) times of 2 to 4 hours. The joint faying surfaces were electroplated with silver prior to bonding. The silver prevented the formation of oxide-film barriers and prevented formation of embrittling phases.

Utilizing these processing parameters, techniques for diffusion bonding of large diameter assemblies were successfully developed and demonstrated by fabrication and testing of four 20-inch diameter joints. Hoop stresses developed during burst testing exceeded the yield strength of the 2219-T62 aluminum alloy. A unique diffusion bonding method was developed utilizing simple differential thermal expansion tooling. The method can be economically adapted to production requirements.

The program established that diffusion bonding is the most satisfactory method for joining large diameter stainless steel to aluminum alloy cylinders and is superior in strength and reliability to welding or brazing.

author

INTRODUCTION

The design of high performance fuel and cryogenic systems for aerospace applications requires efficient and reliable methods for joining dissimilar metal combinations. One of the major dissimilar metal joining requirements is for producing joints between aluminum alloy tankage and stainless steel transfer lines. Aluminum alloys are used for tanks because of their weight advantage while the stainless steels are commonly selected for transfer lines because of their low thermal conductance, good cryogenic properties, and their excellent performance as flexible bellows.

The use of mechanically fastened joints for reliable pressure-tight design of large aluminum to stainless steel parts results in serious size and weight penalties. Processes such as brazing or welding offer the potential of greatly reducing the size and weight of these joints. Small diameter (up to 8-inch) tubular joints between stainless steel and aluminum alloys have been successfully made utilizing soldering, brazing, and welding techniques. However, these methods for joining aluminum to stainless steel result in the formation of embrittling phases at the joint interface. Further development is therefore required, if such processes are to be used in production. Divergent physical properties of the metals such as melting point and coefficient of thermal expansion may also present additional metallurgical and processing difficulties. Furthermore, fabrication characteristics of large diameter (20-inch and greater) joints made by these processes were unknown. The diffusion bonding process appeared to offer excellent potential for joining dissimilar metal tubular sections. Only limited information, however, was available on specific applications of diffusion bonding for aerospace requirements.

Therefore, this development program was undertaken to analyze and evaluate all potential joining methods and to investigate the best process for joining large diameter (20-inch to 50-inch) stainless steel to aluminum alloy parts. The major structural criteria which the resultant dissimilar metal joint had to meet were to withstand thermal shock as well as pressurization at temperatures from 77°F to -423°F.

The approach in the program was to screen and analyze all potential joining methods in the initial phase. Based upon this analysis, the most promising methods were to be selected for experimental evaluation by metallurgical, corrosion, and mechanical property tests in Phase II. The two most promising methods were then to be evaluated as Phase III work for potential production use by fabricating and testing subscale 8-inch diameter test sections. The most structurally reliable method selected from this phase would then be used in Phase IV to fabricate 20-inch diameter joint assemblies under typical production conditions. Also, thermal-shock, leak, and burst tests at room temperature and -320°F were to be conducted in this final phase on the large assemblies. Thorough metallurgical analyses were to be used throughout the program in the evaluation of all methods.

The results of the program are presented in the following sequence:

1. Results and Conclusions
2. Analysis of Joining Methods
3. Process Development
4. Eight-Inch Diameter Test Assemblies
5. Twenty-Inch Diameter Test Assemblies
6. Discussion

RESULTS AND CONCLUSIONS

1. The objectives of this program were successfully accomplished through the use of a diffusion bonding method which utilizes a simple and unique differential thermal expansion tooling. Due to its simplicity, this method should be economically adaptable to the production joining of aluminum-to-steel cylinders up to 50-inch diameter. The successful process parameters were as follows:

Temperature:	500°F to 600°F
Pressure:	20 to 25 KSI
Time:	2 to 4 hours
Diffusion Aid:	Silver electroplating of both faying surfaces

2. Twenty-inch diameter joint assemblies diffusion bonded at 500°F and 600°F successfully passed cyclic pressure tests at RT and -320°F and exhibited burst test pressures up to 670 psig at -320°F. This burst pressure is equivalent to a hoop stress of 53,600 psi which exceeds the yield strength of 2219-T62 aluminum alloy at -320°F. These results demonstrate that steel-to-aluminum joints of high structural integrity can be produced by the diffusion bond method which has been developed.

3. Thermal shock resistance and leak tightness (as determined by helium leak detection of diffusion bonded joints) were successfully demonstrated for the large 20-inch diameter aluminum-to-steel assemblies.

4. Initial investigation of the diffusion bonding parameters established 500°F for 4 hours (and approximately 25 KSI pressure) as the best diffusion bonding cycle. However, on the 8-inch and 20-inch diameter assemblies, sufficient compressive yielding of the aluminum could not be consistently obtained. Therefore, for large diameter parts, 600°F for 2 hours (approximately 20 KSI pressure) was found the most successful. Higher strength tooling materials are required to achieve the full strength potential of joints diffusion bonded at 500°F.

5. Room temperature single and double lap shear strengths greater than approximately 15,000 psi were consistently obtained for the diffusion-bonded flat specimens. At test temperatures of -320°F and -423°F, the joint strengths increased approximately 20% and 30%, respectively.

6. Corrosion testing in tap water as well as 0.1% and 5.0% salt solutions indicates that silver-plated diffusion-bonded joints should be kept free of water or moisture condensation by application of protective coatings or finishes or by use in a low humidity environment.

7. Diffusion-bonded joints are superior in ductility and reliability when compared with joints made by conventional processes such as

welding and brazing. The diffusion bonding method developed permits rigid control of the time-temperature-pressure parameters and effectively controls the formation of embrittling phases at the joint interface.

ANALYSIS OF JOINING METHODS

A survey and analysis of present technology related to the joining of dissimilar metals were conducted. From the analysis, five joining processes which warranted consideration for joining 321 stainless steel to 2219 aluminum alloy were selected. Results of the literature survey are presented in Appendix A. The study revealed that soldering, brazing, fusion welding, electron beam welding and diffusion bonding have been used to join stainless steel to aluminum alloys. Each of these methods will be discussed and analyzed below as applicable to large diameter joints for structural application from 77°F to -423°F.

Stainless steel can be soldered to aluminum alloys by the use of a zinc base solder and an active flux, or by using a tin-lead solder if both metals are electroplated or pretinned prior to making the joint. These processes have the advantage of being accomplished at relatively low temperatures. However, the highest reported joint strengths obtained by soldering are considered inadequate to meet the objectives of this program.

Brazing stainless steel to aluminum is a developed process and is currently being used in several production applications. The Boeing Company has used variations of this process for joining stainless steel to aluminum tubing having diameters ranging from 0.75 inch to 6.0 inch. Satisfactory shear strengths were obtained even though a brittle phase (iron-aluminide) formed at the interface. The effect of this brittle phase was minimized by selecting a joint design which avoided peel type loading. In general, the brazing process requires precoating the stainless steel followed by brazing with the 718 alloy. Brazing temperatures are approximately 1100°F. A major problem inherent in brazing is the difference in coefficients of thermal expansion of the two alloys. Industry results indicate that brazing could be used to join 20-inch diameter stainless steel to aluminum alloy tubing. However, development of the processing techniques would be required to improve joint ductility and to control differential expansion in the large diameter parts.

Fusion welding has been successfully used to join stainless steel to aluminum. Fusion welding requires that the stainless steel be precoated with a metal which will permit wetting during welding. The formation of brittle intermetallics at the interface are difficult to control. Joints up to six inches in diameter have been produced by this method at Boeing. Joint quality is directly dependent on the weldor's capability to control fusion. Application of this process to reliable production of large diameter joints would require precoating and fusion welding control evaluations.

The electron beam welding process was evaluated by The Boeing Company on the X-20 program for joining stainless steel to aluminum. In this work a square butt groove joint with copper transition material was used. However, a continuous intergranular network of $CuAl_2$ formed at the interface resulting in a brittle joint. Lap joints, requiring fillet welds are not readily amenable to electron beam welding due to difficulty in obtaining adequate fillet size. The electron beam welding process does not appear feasible for joining large-diameter dissimilar-metal joints.

Stainless steel has been successfully diffusion bonded to aluminum alloys as described in U. S. Patent 2,908,073 and by other investigators. The major advantage of this process is that it can produce void-free joints having high strength and good ductility. The joints contain a minimum of brittle intermediate phases due to the low bonding temperatures (600°-900°F) and short times used. The major disadvantage of the process, as developed, is the high deformation or plastic flow of the aluminum which is required to break the oxide film on the surfaces of the metals being joined. Based on this study, diffusion bonding appeared to offer growth potential for joining steel to aluminum. Considerable work, however, would be required to develop techniques and tooling for 20-inch diameter tubular joints.

Based on the foregoing study and analysis, the three most promising processes for joining large diameter stainless steel to aluminum alloy tube joints were selected for further development. These were (1) fusion welding, (2) brazing and (3) diffusion bonding.

A study was then conducted to select the most desirable joint design for comparative evaluation of these three joining processes. A lap type joint was selected in order to obtain maximum joint strength for this application.

Figure 1 shows that 2219 aluminum alloy has a thermal contraction which is approximately 30% greater than stainless steel. Due to the greater contraction of the aluminum alloy at the lower service temperature range (77°F to -423°F) the aluminum should be on the outer surface to give the most reliable joint. The joint configurations selected for each of the processes are shown in Figure 2.

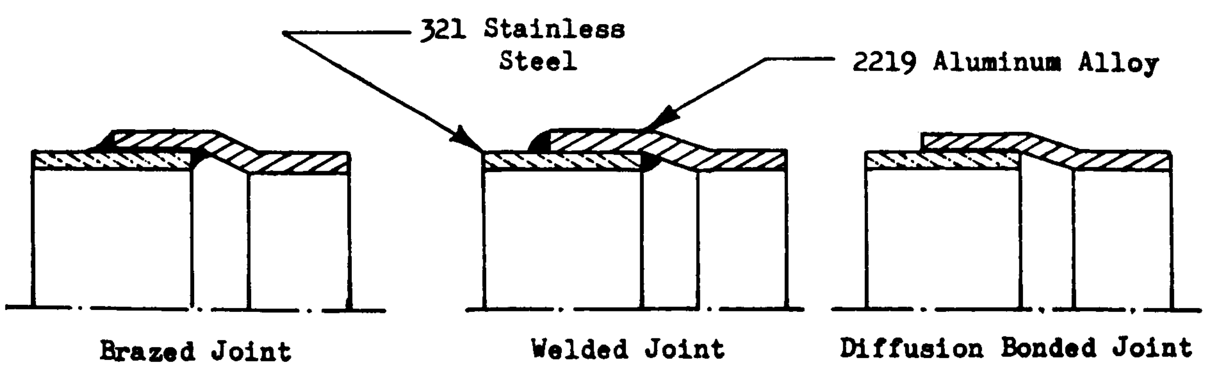


FIGURE 2:

JOINT DESIGN FOR BRAZING, WELDING AND DIFFUSION BONDING

The joints were designed to have an overlap of approximately 1.0 inch. This type of joint prevents the entrapment of corrosive cleaning solutions and foreign particles in the joint faying surface and allows for variation of joint interface area depending on the shear strength required.

PROCESS DEVELOPMENT

An investigation was conducted to determine the best techniques for joining 321 stainless steel to 2219 aluminum alloy by brazing, fusion welding and diffusion bonding. The goals of this investigation were: (1) to develop techniques which would improve the ductility of brazed and welded joints, and (2) to develop diffusion bonding methods applicable for joining large diameter cylinders.

The test work was conducted in two phases; preliminary and final process development. In the first phase a preliminary investigation was made on the three joining processes to evaluate the effect of various techniques on the metallurgical characteristics and mechanical properties of joints. In the second phase, the two selected processes were refined for production application, and were further evaluated by mechanical and corrosion testing.

PRELIMINARY PROCESS DEVELOPMENT

BRAZING

A review of brazing processes indicated that dip brazing was the best and most commonly used method for producing brazed lap joints. However, no suitable brazing alloy has been developed which will permit dip brazing of the 2219 aluminum alloy. Due to the low melting point of the 2XXX series Al-Cu alloys, they cannot be dip brazed with presently available brazing alloys. Therefore, the 6061 aluminum alloy, which is compatible with the required process temperature, was used in subsequent brazing investigations. The 6061 aluminum alloy could be fusion welded to 2219 and therefore used as a transition tube between the stainless steel ring and the 2219 tube assembly.

In general, the stainless steel must be coated prior to brazing with a metal which will promote the necessary wetting action. Previously, The Boeing Company had evaluated an aluminizing process for this purpose. Dipping the stainless steel in molten 1100 aluminum alloy at 1300°F produced an aluminized surface which contained a thick iron-aluminide zone at the steel-aluminum interface as shown in Figure 3A. This coating permitted braze joints between stainless steel and aluminum to be made which exhibited shear strengths of 15,000 to 20,000 psi. However, the joints were extremely brittle in a peel test.

The objective of the brazing investigations conducted during this program was to control the formation of brittle intermetallic phases in the braze joint. Since the formation of excessive iron-aluminide appeared to be unavoidable in the aluminizing process previously described, the aluminizing process was avoided by using 0.0005-inch thick electroplatings of various metals which would wet or alloy with 718 aluminum braze alloy at 1100°F. Silver, copper, tin and zinc were chosen as electroplate materials. Preheated specimens were brazed at 1100°F in Parke "E" flux for 2 minutes. The tests showed that silver, copper and tin permitted good wetting and filleting during brazing. The zinc plating did not permit proper wetting of the steel.

Peel testing of the brazed specimens, which were silver, tin or copper preplated, resulted in a failure occurring randomly through the braze alloy and through the diffusion zone at the surface of the steel. Considerable deformation of the aluminum side of the lap joint occurred during peel testing. Metallographic examination of these brazed specimens showed that all contained a relatively thin diffusion zone. The photomicrograph on Figure 3B shows the narrow diffusion zone of a copper plated brazed specimen, and is typical of that produced by tin and silver plated surfaces.

The results of these tests indicate that a more ductile brazed joint is produced by initially electroplating with silver, copper or tin than by the previous process of aluminizing with 1100 aluminum alloy. Utilization of this dip brazing process, however, for large diameter joints would require considerable tooling and process development because problems associated with the thermal expansion differences and the relatively long time at brazing temperature.

FUSION WELDING

As in the brazing process, fusion welding requires that the stainless steel be precoated with a metal which will permit wetting by a molten aluminum alloy during joining of stainless steel to aluminum. The Boeing Company had previously used an aluminizing process for this purpose wherein the stainless steel was dipped into molten 1100 aluminum alloy at 1300°F. This method produces a relatively thick diffusion zone containing brittle iron-aluminides. Because the total aluminized layer is thin with respect to the size of the joint, subsequent welding caused further iron-aluminide development. Considerable difficulty with underbead cracking had previously been encountered during welding due to the influence of these brittle intermetallics. It was evident that an improvement in the process for precoating the stainless steel was needed for the successful application of fusion welding to this program. Methods for applying a thick aluminum coating having a minimum of iron-aluminide at the steel interface were investigated prior to the evaluation of fusion welding.

Aluminizing

The investigation of aluminizing processes consisted of a comparison of the manual application of 718 aluminum alloy, as well as the application of 718 and 1100 aluminum alloys by plasma arc spraying, to the dipping process for the production of an aluminized layer. Specimens with electrolytic preplatings .0005 inches thick of silver, copper, tin, and zinc as well as unplated stainless steel were used in each process. The techniques used for the three processes for aluminizing, i.e., dipping, manual and plasma arc, are described below.

The photomicrographs shown in Figure 6 illustrate typical coatings produced by plasma arc spraying:

Figure 6A shows a photomicrograph of an aluminized, copper-preplated, stainless steel specimen which was diffusion heat treated in an 1150°F salt bath after plasma arc spraying. The coating shown consists of an aluminum-copper hypereutectic structure with a thin, complex, iron-aluminide diffusion zone between the coating and the stainless steel base metal. During the bend test, cracks initiated in the coating and propagated through the iron-aluminide diffusion zone.

Figure 6B shows a photomicrograph of an aluminized, silver-preplated, stainless steel specimen diffusion heat treated in an 1150°F salt bath after spraying. The coating shown consists of an aluminum-silver hypereutectic structure. Small cracks occurred in the complex iron-aluminide diffusion zone between the coating and the stainless steel base metal.

Welding

The 2219 aluminum alloy was fillet welded to aluminized 321 steel. Prior to welding, the steel had been aluminized both by dipping in flux covered,molten 1100 aluminum (1300-1325°F - 15 sec.) and by manual application of 718 aluminum alloy to flux coated 321 steel. During manual application, the steel was heated by conduction from a heated copper mandrel. The 718 alloy was applied within 30 seconds while the steel was at a temperature of approximately 1100°F. Fillet welds were made manually with 4043 aluminum alloy filler wire by the GTA method using an AC power supply.

The welded specimens were peel tested to determine the adherence of the aluminized coating. The fillet weld of the specimens aluminized by the manual process with the 718 aluminum alloy failed through the throat of the weld. Fracture occurred in the weld metal with the aluminized coating remaining on the steel. In contrast, the weld specimens which had been aluminized by the dip process with 1100 alloy at 1300°F failed by peeling at the aluminum coating-steel interface. Fracture was through the brittle iron-aluminide diffusion zone. The results indicate that the aluminizing process which used the manual application of the silicon rich 718 alloy will result in a more ductile and more reliable weld because of the suppression of the formation of the iron-aluminide phase.

The application of 1100 aluminum alloy was accomplished by dipping the stainless steel in a flux covered, molten 1100 aluminum alloy bath for 15 seconds at 1300-1325°F.

Manual application of the 718 aluminum alloy was accomplished by heating flux covered specimens to 1100 ± 25°F. Both quartz lamps and an oxyacetylene flame were evaluated as heat sources.

Application of 718 and 1100 aluminum alloys by plasma arc spraying was followed by diffusion heat treatment. Diffusion treatment temperatures ranged from 1000°F to 1150°F for times of 30 seconds to five minutes. One series of specimens was heated in molten brazing salt, a second was heated by quartz lamps in air, and a third was heated in a furnace retort with an argon gas atmosphere.

After aluminizing, the specimens were bent to a one inch radius and examined metallographically to determine the diffusion zone characteristics and the ductility of the coating. The results of the metallurgical investigation are shown in Table I.

The evaluation of these tests is summarized below.

All specimens aluminized by the dip coating process, whether bare condition or preplated prior to aluminizing, were brittle and produced cracks during bend testing. In all cases a broad iron-aluminide diffusion zone developed which was responsible for the cracks. Figure 4 shows a typical microstructure of an aluminum coating produced by this process. Regardless of surface preparation used, the stainless steel could not be satisfactorily aluminized with the 1100 aluminum alloy because of the rapid formation of iron-aluminide which embrittles the coating.

The specimens on which 718 aluminum alloy had been manually applied to flux coated stainless steel showed satisfactorily aluminized surfaces. Figure 5 shows the microstructure of a 321 stainless steel specimen aluminized by this method. The coating consists of a coarse eutectic structure which is more ductile than the iron-aluminide phase produced by the process of dip coating with 1100 alloy at 1300°F. The influences of short time, lower process temperature, and high silicon composition of the 718 alloy combine to suppress the formation of the brittle iron-aluminide intermetallic. Practically no diffusion can be observed between the stainless steel and the aluminum coating. The coating proved to be ductile during the bend test. This process appears to be the most feasible for aluminizing stainless steel.

The plasma arc method produced an unsatisfactory coating regardless of the type of electroplated surfaces or diffusion heat treatment used. In a majority of the tests conducted, the coatings failed in the bend test because of poor ductility. Examination of the coated specimens showed poor wetting of the steel resulting in uncoated areas.

DIFFUSION BONDING

Diffusion bonding requires that the joint materials be in intimate contact and that the parameters of time, temperature and pressure be critically controlled to permit interdiffusion of atoms across the joint interface. Generally, the higher the temperature, the lower the time and pressure required. In the application of diffusion bonding for joining large diameter cylinders, the magnitude of the pressure must be minimized to (1) prevent excessive compressive yielding of the structural aluminum component and (2) to allow for design of tooling which is not too massive and complex.

Other investigators have reported obtaining acceptable, void-free aluminum-to-steel joints when using deformation as high as 25 per cent of the aluminum thickness. However, in order to reduce pressure and the resultant compressive yielding of aluminum, a new approach was required for the application of diffusion bonding to large diameter assemblies.

The following describes the preliminary investigation to determine methods for adapting the diffusion bonding process to joining large diameter 321 stainless steel to 2219 aluminum alloy parts.

Tooling Analysis

Prior to starting the diffusion bonding process development, a study was made to determine fabricating methods by which bonding pressure could be applied to a 20-inch diameter diffusion bonded joint having a 1.0-inch overlap. This study revealed that the best method was to use tooling which could apply this pressure by means of differential thermal expansion of the tooling materials. Figure 7 shows the arrangement of the tooling and parts for this method.

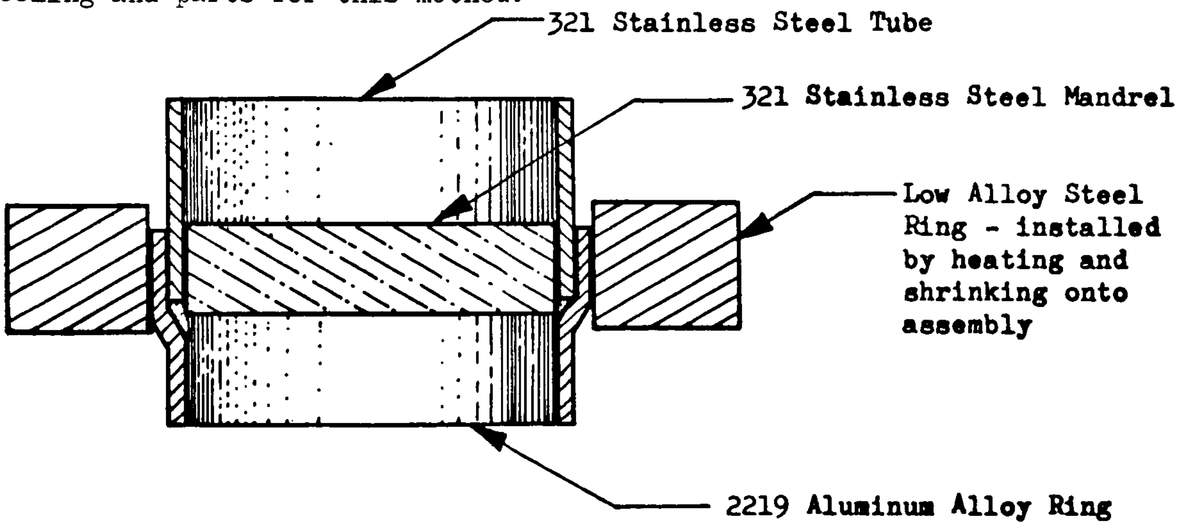


FIGURE 7: DIFFERENTIAL THERMAL EXPANSION TOOLING ARRANGEMENT FOR TUBULAR JOINTS

The inner mandrel of 321 stainless steel has a linear thermal expansion (77°F-900°F) approximately 50% greater than the low alloy steel outer mandrel, (Figure 1). From this, calculations showed that the 20-inch diameter stainless steel has a free diametric expansion (no pressure) which is approximately 0.030-inch greater than the low alloy steel restraining ring at a 600°F temperature. However, during actual bonding, the compressive pressure on the 321 stainless steel mandrel would prevent this total expansion from occurring. Likewise, the bonding pressure places the external alloy steel ring in hoop tension and results in the ring expanding to a diameter greater than which would occur during its free expansion at 600°F. Using equations which predict stress and strain for cylinders under external and internal pressure, calculations showed that to create an internal bonding pressure which approximates the compressive yield strength of the 2219-T62, the outer restraining ring must be installed using a shrink fit. This interference fit is required to provide a preload to supplement the pressure from the differential expansion of the tooling. The actual amount of interference fit will depend upon bonding temperatures and the actual width and diameters of the tooling.

Bonding of Bare Material

The diffusion bonding parameter development was initially performed on bare material. The work was accomplished in an air atmosphere utilizing a hydraulic press with heated platens. Prior to bonding, the material was degreased, abrasive cleaned, and wiped with MEK. The material was immediately placed in the press (cold platens) and a pressure of 21,400 psi was applied to the specimen. The platens were heated to 600°F (15 minute heat-up time) and the specimens were held at temperature for 1.5 and 4.0 hours. The results, summarized in Table II, show the specimens had very low shear strength.

Attempts were also made to diffusion bond bare material (cleaned as explained previously) in an argon atmosphere using the differential expansion press shown in Figure 8. Bonding was attempted at 600°F and 900°F. Peel testing of these specimens showed virtually no diffusion bonding had occurred.

The only technique by which bare material was satisfactorily diffusion bonded involved utilization of the techniques described in Alcoa U. S. Patent 2,908,073. The material was cleaned as previously explained and placed between platens of the hydraulic press at 15,000 psi pressure. When the temperature of the specimen reached 700°F, the pressure was rapidly increased to cause the aluminum to flow and reduce in thickness by 25 per cent. The rapid plastic flow of the aluminum evidently destroys the surface oxide films and permits solid state diffusion to occur as shown in Figure 9. Specimens produced by this manner showed good strength and ductility.

Bonding Using Diffusion Aids

Although bare material was satisfactorily diffusion bonded, as described above, this method cannot be considered for 20-inch diameter tubing because the differential thermal expansion tooling is not capable of producing the high deformation required. Consequently, diffusion bonding was evaluated using interface diffusion aids in an attempt to obtain good bonds without excessive deformation of the aluminum.

a. Copper Plating

Initially, both the stainless steel and aluminum were copper plated at the faying surfaces to be joined. Prior to bonding, the copper plate was cleaned by light abrasive cleaning, followed by wiping with MEK. Specimens bonded at 500°F for 3 hours (in air using the hydraulic press with heated platens) showed good properties in peel testing. In these tests the initial hydraulic pressure applied to the specimens effectively sealed the plated surfaces from oxidation during heating and bonding. Subsequent work, however, showed that the copper plating easily oxidizes in air preventing effective solid state diffusion. Copper electroplating was not investigated further because it was anticipated that the plating could not be kept free of oxides during assembly of the 20-inch diameter parts into the preheated external tooling ring as described in the tooling analysis section.

b. Silver Plating

Diffusion bonding was accomplished using silver plating on the joint faces of the stainless steel and 2219 aluminum alloy. The detailed procedure used for plating is outlined in Appendix B. A nickel strike was used prior to silver plating the stainless steel. In the case of aluminum, light zinc flash and a copper flash were used prior to silver plating. The nickel strike on the stainless steel and the zinc and copper flash plating on the aluminum alloy are conventional plating techniques used to provide proper adherence of the silver plating. Bonding was accomplished in air using the hydraulic press and heated platens as previously described. Prior to bonding, the plated surfaces were lightly cleaned with an abrasive and wiped with acetone. Bonding was initially performed at 500°F and 600°F using various bonding pressures and times. These temperatures were chosen because the yield strength of the 2219-T62 alloy at these temperatures is fairly low, thus minimizing the bonding pressure required. In addition, the room temperature ultimate strength of the alloy is reduced only about 15% after exposure at these temperatures.

The results of these tests, as shown in Table II, reveal that good shear strengths were obtained. Only slight deformation (.003 to .005-inch) of the aluminum was required to achieve void-free diffusion bonds. Figure 10 shows photomicrographs of a diffusion bond accomplished at 500°F for 3.5 hours. The microstructure revealed that complete solid state diffusion had occurred across the silver-silver joint interface.

Figure 11 shows a microprobe analysis of the diffusion bonded joint. The analysis shows slight diffusion of the silver into the aluminum and practically no diffusion of the silver into the stainless steel.

The use of silver plating as a diffusion aid proved very satisfactory. The silver has a high tolerance of contamination and resistance to oxidation during diffusion bonding. Tests showed that after the silver plated surfaces were cleaned, they could be exposed to a temperature of 500°F in air for 30 minutes and then be satisfactorily joined by diffusion bonding without additional cleaning. These results showed that the parts and tooling could be heated in air for shrink fit assembly without contamination of the silver plated surfaces.

PRELIMINARY PROCESS SELECTION

At the conclusion of the preliminary development work, two processes were selected for further development. Of the three processes carried into preliminary development - brazing, welding, and diffusion bonding - the diffusion bonding process offered the greatest potential of minimizing the occurrence of brittle phases at the joint interface. Fusion welding was selected over brazing as the second process for additional development because (1) of the difficulty of applying the brazing process to 20-inch diameter assemblies and (2) dip brazing could not be used on the 2219 aluminum alloy.

FINAL PROCESS DEVELOPMENT

The preliminary process development phase resulted in the selection of fusion welding and diffusion bonding as the processes to be carried forward into additional development. In the preliminary phase, process parameters were investigated to the extent necessary for selection of the two best processes. Additional development was then necessary to establish the point where process time and temperature requirements could be adequately specified for subsequent fabrication of 8-inch diameter test parts. Accordingly, the final process development phase had as its objectives the following:

1. Determination of time-temperature requirements for the process of manual aluminizing of stainless steel with 718 aluminum alloy. (This process was previously selected as the best method of precoating of the stainless steel prior to welding).

2. Optimization of time-temperature parameters and techniques for diffusion bonding.

3. Determination of shear strength of fusion welded and diffusion bonded specimens.

4. Examination of the corrosion behavior of welded and diffusion bonded joints.

ALUMINIZING

The preliminary development work had shown that flux coated 321 stainless steel could be satisfactorily manually aluminized with 718 aluminum alloy. Coatings produced by this method will sustain a 10T bend radius without cracking provided the diffusion zone thickness at the aluminum-stainless steel interface does not exceed .0002-inch. Additional tests were therefore performed to determine the relationship between diffusion zone thickness and time at the 1100 ± 25°F aluminizing temperature. These tests were made on two-inch squares of .060-inch thick 321 stainless steel which had been coated with Jensen Alloy Co. No. 227 flux. The specimens were heated with an oxyacetylene flame to 1100 ± 25°F, manually aluminized with 718 aluminum alloy, and held at temperature for times ranging from 15 seconds to 2 minutes. The time-temperature profile for each specimen was recorded. The results, as tabulated in Figure 12, show that aluminized stainless steel should not be held at the aluminizing temperature for longer than 30 seconds. This requirement will insure that the iron-aluminide formation will not exceed .0002-inch.

DIFFUSION BONDING

It was observed in preliminary evaluation that peel test specimens occasionally failed at the silver-stainless steel interface. An investigation was therefore conducted to determine if an electroplated layer of copper between the stainless steel and silver would improve the peel resistance of that portion of the diffusion bonded joint. Stainless steel specimens were prepared using a copper plating thickness of 0.0004 to 0.0006-inch. The copper plate was then covered with a silver plating 0.0004 to 0.0005-inch thick. Preparation of the aluminum specimens by silver plating, as well as diffusion bonding of stainless steel to aluminum test joints, was accomplished in the same manner previously described during preliminary process development. Metallographic examination of peel-tested joints showed that all failures occurred in a random manner through the silver-to-silver interface or in the silver-aluminum interface. The results indicated that the use of the copper undercoat eliminated peel failure at the stainless steel to the electroplated interface.

A series of test joints were then prepared for diffusion bonding at various times and temperatures. The specimens were plated by the procedure shown in Appendix C, which describes in detail the pre-bonding preparation adopted as a result of the investigation described above. The differential thermal expansion press shown in Figure 8 was used to make the bonds. The process was performed in an air atmosphere oven. Temperatures were measured by a thermocouple between the specimen and die face. Specimens were diffusion bonded at the following times and temperatures:

Temperature °F	Time						
	5 min.	20 min.	1 hr.	2 hr.	3 hr.	4 hr.	14 hrs.
375							X
400						X	
500			X	X	X	X	
600			X	X			
700	X	X					

The times shown are for the period during which the joint was at the specified temperature. Approximately one hour was required to heat the specimen from room temperature to the bonding temperature used. The compressive deformation of the aluminum measured after bonding ranged from 3% of the thickness at a 400°F bonding temperature to 7% at 700°F.

Following bonding, the specimens were peel tested at -320°F. These tests showed that a bonding cycle of 500°F for 4 hours gave the highest indicated strength and developed the greatest deformation of the aluminum component prior to failure. Specimens bonded at 600°F for 1 or 2 hours also exhibited considerable deformation prior to failure. Acceptable strengths were obtained. The remainder of the specimens did not provide acceptable strength and ductility in peel testing.

A metallographic examination was also made on the diffusion bonded specimens. The specimens were mounted at an angle of 15° so that the thickness of the diffusion bonded zone could be amplified. The diffusion zone was effectively magnified approximately four times greater than that obtained with a conventional 90° mounting angle. This technique was used to aid metallographic examination. The results of this examination are summarized as follows:

a. The microstructure of the copper to stainless steel interface after plating and prior to diffusion bonding is shown in Figure 13A. The photomicrograph illustrates the extent of intergranular penetration by the copper into the stainless steel during plating. This copper to stainless steel interface exhibited a similar appearance after diffusion bonding at temperatures up to 700°F.

b. The silver to silver joint interface had been completely bonded at all the time-temperature combinations investigated. This zone consists of fine grained-recrystallized silver and shows complete, void-free solid state diffusion at the original joint interface.

c. Optical microscopy did not disclose solid state diffusion between the copper-silver or copper-stainless steel interfaces although diffusion at these interfaces can be assumed.

d. The zone between the 2219 base metal and the silver plating contained a .00002-inch thick copper strike prior to diffusion bonding, as shown in Figure 13B. Control of diffusion in this zone is critical in obtaining optimum joint properties. Inadequate diffusion in this zone will result in low strength, whereas excessive diffusion will result in the formation of complex copper-silver-aluminum intermetallics which embrittle the joint. At 400°F, practically no diffusion could be observed. At 500°F, a diffusion zone approximately twice as thick as the original copper strike developed. Additional diffusion occurs with increasing temperature. At 700°F, diffusion is excessive. Typical photomicrographs of the diffusion zone between the 2219 aluminum and silver plating are shown in Figure 14. Based on this evidence, a bonding temperature of 500°F to 600°F will permit adequate diffusion to develop joint strength and minimize the formation of embrittling intermetallic phases.

MECHANICAL TESTING

Single and double lap shear specimens were joined by fusion welding and by diffusion bonding. Specimen configurations are shown in Figure 15. Photographs of typical specimens are shown in Figure 16.

The welded specimens were made by aluminizing the steel with 718 aluminum alloy, as explained in the previous section, followed by welding with 4043 filler metal.

Two groups of diffusion bonded specimens were tested. The first group was diffusion bonded at 600°F for 2 hours using the platen press and plating procedure (Appendix B) described in the preliminary process development section. Stops were placed between the press platens to limit compressive yielding to a 0.004 to 0.005-inch range. The second group was diffusion bonded at 600°F for 2 hours using the differential expansion press and plating procedure (Appendix C) described in the final process development section. The aluminum alloy components of these specimens were compressively yielded 0.005 to 0.006 inch.

Three single and three double lap specimens were tested at room temperature, -320°F, and -423°F for each joining method. The resulting shear strengths are shown in Table III. These results indicate that room temperature shear strengths above approximately 15,000 psi can be consistently obtained by both the diffusion bonding and GTA welding methods. A maximum value of 24,000 and a minimum of 14,280 psi was obtained for all test conditions. Except for the single lap GTA welds, the other joints had significantly higher properties at -320°F than at room temperature. The -423°F results were not significantly different from -320°F results.

After testing, the shear specimens were examined visually and metallographically to determine the nature of the joint failures. The results of this examination were as follows:

1. The single lap welded specimens, when tested at room temperature, failed primarily through the throat of the weld fillet. When tested at -320°F and at -423°F, the specimens failed by a combination of shearing as well as peeling in the weld metal on the aluminized steel interface. Figure 17A illustrates typical failure modes of the single lap welded joints.

2. The double lap welded specimens, when tested at room temperature, failed primarily through the throat of the weld fillet. When tested at -320°F and at -423°F, the failure occurred at the aluminized surface of the stainless steel. Figure 17B illustrates typical failure modes of the double lap welded joints.

3. The single lap diffusion bonded specimens, regardless of test temperature, failed randomly by shear through the original silver-silver interface or by peeling through the silver-aluminum diffusion zone. The photomicrograph shown in Figure 18A illustrates a peel type failure of a single lap joint. The double lap diffusion bonded specimens, regardless of test temperature, failed primarily by shear through the silver bond. This type of failure is illustrated in Figure 18B.

4. There is no apparent difference in joint strength or failure mode between the two groups of diffusion bonded specimens.

CORROSION TESTING

Corrosion testing was performed on fillet welded and diffusion bonded 2219 aluminum alloy to 321 stainless steel lap joints. Tests were conducted in a 5% NaCl spray per Federal Test Method Standard 151, Method 811.1.

Three types of fillet welded lap joints (using three precoat methods) and one type of diffusion bonded lap joint (silver plated per Appendix C) were prepared and tested as outlined in Table IV.

The joints were metallurgically examined after 72, 144 and 360 hours of exposure. The specimens were examined for the type, location and depth of corrosion. A summary of the results is as follows:

1. All the fillet welded specimens revealed moderate pitting corrosion of the 4043 aluminum filler alloy and exhibited severe corrosion at the interface of the 4043 fillet weld and the stainless steel. Figures 19A and 19B show pitting corrosion after 72 and 144 hours exposure. At the end of 360 hours the corrosion had penetrated completely through the fillet weld.

2. The diffusion bonded specimens exhibited severe corrosion at the point where the silver coating terminated on the aluminum surface. A typical example is shown in Figure 20A. After 360 hours, corrosion had almost penetrated through the .125-inch thick aluminum. The silver coating did, however, protect the joint interface from corrosion as shown in Figure 20B.

Based on the above results, it is evident that the 5 per cent salt spray environment is too severe for the 321 stainless steel to 2219 aluminum alloy dissimilar metal joint.

Additional testing was performed on single lap welded and diffusion bonded specimens by immersing for 14 days in (1) tap water and in (2) distilled water containing 0.1% NaCl. The specimens were placed on their edge and the level of the water was adjusted so the upper half of the specimens remained in the air. After 14 days all specimens showed discoloration of the aluminum. All specimens showed slight pitting at the point where the silver coating terminated on the aluminum surface or at the toe of the fillet weld. The specimens immersed in the distilled water + 0.1% NaCl showed slightly more pitting than those immersed in tap water.

The results of the corrosion testing indicate that 321 stainless steel to 2219 aluminum alloy joints should be protected by protective finishes, or kept in a controlled, low humidity environment.

SUMMARY

The final process development investigation resulted in the development of the diffusion bonding and fusion welding methods, which can be adapted for the fabrication of large diameter 321 stainless steel to 2219 aluminum alloy assemblies.

EIGHT-INCH DIAMETER TEST ASSEMBLIES

The purpose of the subscale 8-inch diameter tank fabrication and testing was to determine if the two selected processes, diffusion bonding and fusion welding, could be successfully adapted to production applications. The results of this work were used, in conjunction with the previous development work, to select the best method for joining 20-inch diameter test assemblies.

This portion of the report will be discussed under two major headings:

1. Fabrication of Eight-Inch Diameter Test Assemblies
2. Burst-Testing of Eight-Inch Diameter Test Assemblies

FABRICATION OF EIGHT-INCH DIAMETER TEST ASSEMBLIES

GTA FUSION WELDED TEST ASSEMBLIES

An 8-inch diameter fusion welded tank was fabricated by initially fusion welding two machined 321 stainless steel and 2219-T62 aluminum alloy rings (each 2 inches long). A cross section of the joint is shown in Figure 21A. The fabrication of the rings by GTA fusion welding consisted of two distinct and separate steps, (1) aluminizing and (2) welding. These steps will be discussed below.

Procedure

a. Aluminizing

Prior to welding, the bevel and groove of the stainless steel ring were aluminized with 718 aluminum alloy as shown in Figure 21A. This was accomplished by coating the wire brushed surface of the stainless steel with No. 227 Flux (Jensen Alloy Co.) and heating the ring with an oxyacetylene torch on the inner surface. While the ring was rotated slowly, 718 aluminum alloy in wire form was manually applied to the bevel and groove of the ring. Temperature measurements showed that the steel ring reached a maximum temperature of 1100°F for approximately 15 seconds during aluminizing. The thickness of the 718 aluminum braze alloy after aluminizing varied from 0.015 to 0.020-inch. The part was then chemically cleaned to neutralize the flux. The aluminized coating was then machined to a uniform thickness (0.008-0.010-inch) to permit assembly of the aluminum ring to the aluminized stainless steel.

b. Welding

The aluminum ring was manually fillet welded to the aluminized stainless steel ring, using the AC-GTA welding process and 4043 filler metal. During welding, the arc was maintained primarily on the aluminum to prevent excessive melting of the aluminized coating.

Results

After welding, the ring assembly was inspected with a helium leak detector and found leak tight. A photograph of the welded ring assembly is shown in Figure 22B.

Study of the ring fabrication by the fusion welding process indicated that the process would be difficult to adapt to production applications. The major limitation is that the aluminizing and welding processes would probably have to be conducted manually by a skilled weldor. Limited studies to determine the feasibility of mechanizing either or both of the aluminizing or welding processes proved unsuccessful. During welding, it was found mandatory to continually manipulate the arc in order to obtain a satisfactory fillet weld and minimize heat-input at the aluminum-steel interface.

DIFFUSION BONDED TEST ASSEMBLIES

The diffusion bonded tanks were fabricated by first machining and plating 321 stainless steel and 2219-T62 aluminum alloy rings (each 2-inch long). A total of four diffusion bonded rings were manufactured. The first ring assembly had a configuration as shown in Figure 21B. The stainless steel ring was beveled to permit a smooth inside transition between the aluminum and steel. However, difficulty in matching the bevels on the initial tank resulted in discontinuing this configuration. The remaining three rings were machined as shown in Figure 21C. The diffusion bonding procedure and results are discussed below.

Procedure

Prior to diffusion bonding, the faying surfaces of the 321 stainless steel and 2219 aluminum alloy were silver plated using the procedures described in Appendix C. The rings and tooling were assembled as shown in Figure 23. The steel and aluminum rings were machined to dimensions with a 0.002-inch interference fit to assemble them onto the inner mandrel. Prior to assembly, the plated surfaces were subjected to light abrasive cleaning and by wiping with acetone. The rings were then heated to 250°F in air and without additional cleaning were installed onto the inner 321 stainless steel mandrel. The outer 4340 alloy steel ring (machined to provide a 0.008 to 0.012-inch shrink fit) was heated to 600°F and installed around the diffusion bonded assembly. The entire assembly was then held at room temperature until all parts stabilized at temperature (approximately 250°F). The assembly was then placed into an air atmosphere furnace for diffusion bonding at the desired time and temperature.

After diffusion bonding, the assembly was air cooled and the inner mandrel and outer ring were removed by cooling with liquid nitrogen. This procedure is explained in detail during discussion of the 20-inch diameter assemblies in a later section of this report. A photograph of the bonded ring is shown in Figure 22A.

Results

The following describes the specific diffusion bonding cycle, examination and helium leak testing of ring assemblies.

(1) Ring Assembly No. 1

The first assembly was diffusion bonded at 500°F for 4 hours. An additional hour (total of 5 hours) was used to thermally stabilize the assembly. This one hour temperature stabilization time was used on all subsequent diffusion bonded assemblies. Examination of the assembly after bonding revealed the joint overlap varied from 0.85 to 1.0 inch. This was caused by misalignment of the assembly before the outer ring had cooled sufficiently during the shrink fit operation. To correct this misalignment, a large flat plate and positive stop were used during assembly of the remaining diffusion bonded rings. Measurement of the assembly showed the aluminum ring had compressively yielded 0.002 to 0.003-inch in wall thickness. The ring was leak tight when inspected with a helium leak detector.

(2) Ring Assembly No. 2

The second ring assembly was diffusion bonded at 500°F for 4 hours. After diffusion bonding, measurements showed that the 2219 aluminum ring had compressively yielded 0.003-inch in wall thickness. The ring was then helium leak checked and was found to leak in two areas. The areas were approximately 2.5 inch long and were located 180 degrees apart. The ring was then rebonded at 650°F - 1 hour. Measurements showed that the 2219 aluminum had compressively yielded approximately 0.005-inch in wall thickness. Leak checking showed the same two areas leaked. The ring was then thermally shocked ten times in LN_2. Subsequent leak checking showed that the same two areas leaked but did not enlarge in length. The ring was then cut into sections for peel testing and metallurgical examination. The following results were observed:

a. The two areas which leaked did not diffusion bond because they were not in contact. This lack of contact was caused by thinning of the 321 stainless steel ring due to deflection during machining. The wall thickness of the stainless steel ring in the two areas was reduced by 0.012 inch. An internal support was used on the remaining 321 stainless steel rings to circumvent this problem.

b. Peel testing of the diffusion bonded sections of the ring (at room temperature) showed the joint to possess excellent toughness. Considerable deformation of the stainless steel was required to accomplish joint peeling.

c. Metallurgical examination of a diffusion bonded section of the joint showed it to be void free. Adequate diffusion at the silver to silver interfaces had occurred. Figure 24A shows the appearance of the diffusion bonded joint.

d. Metallurgical examination of the diffusion bonded joint after peeling showed that the failure occurred randomly through the silver-silver and/or through the silver-aluminum interfaces. Figure 24B illustrates the appearance of the joint after peeling.

(3) Ring Assembly No. 3

Measurements of the first two ring assemblies (bonded at 500°F - 4 hours) indicated that the amount of compressive yielding of the aluminum ring was marginal to insure 100% diffusion bonded joints. The third ring was diffusion bonded at 600°F for 2 hours to increase the amount of compressive yielding.

After bonding, measurements showed the aluminum ring had compressively yielded, reducing the wall thickness by .005-inch. The ring was thermally shocked ten times (from room temperature) in liquid nitrogen and was still found leak tight as determined by the helium leak detector. Ultrasonic and dye penetrant inspection did not reveal any unbonded areas.

(4) Ring Assembly No. 4

The fourth ring was diffusion bonded at 600°F for 1 hour. The aluminum ring compressively yielded 0.005-inch in wall thickness. The ring was found helium leak-tight after thermally shock testing ten times in liquid nitrogen. Ultrasonic and dye penetrant inspection did not reveal any unbonded areas. This ring assembly was retained as a sample for the program sponsor.

Diffusion bonded ring assemblies No. 1 and 3 were fabricated into tanks for burst testing at room temperature and -320°F, respectively.

The results of the tank fabrication studies by the diffusion bonding process indicated that the developed process could be readily adapted to production applications. The problem areas initially encountered in this study, i.e., assembly misalignment and wall thinning due to machining, were readily corrected by further development.

BURST TESTING OF EIGHT-INCH DIAMETER TANKS

FUSION WELDED TANK

The fusion welded ring assembly was welded into a tank assembly having a configuration as shown in Figure 25 and was hydrostatically burst tested at room temperature. The tank failed in the steel to aluminum fillet weld at 650 psig. This corresponds to a hoop tensile stress of 27,200 psi and a weld shear load of approximately 1360 pounds per inch. A photograph of the tank after the burst test is shown in Figure 26.

The tank failure originated in the throat of the circumferential fillet weld, and propagated through the weld for approximately 180° of the circumference. The remainder of the weld failed by the fillet peeling from the aluminized surface. The fillet throat depth in the area of the failure was approximately 0.100 inches. Based on this information, the fillet shear stress due to the pressure vessel end load was approximately 13,600 psi. The average fillet shear stress obtained from uniaxial specimens, Table III, was 17,613 psi. Based upon this figure, the tank failed near the ultimate load carrying capability of the circumferential fillet weld. Therefore, the potential for increasing the hoop tensile stress of the GTA fusion welded assembly would be very limited.

DIFFUSION BONDED TANKS

Ring assemblies No. 1 and No. 3 were welded into a tank assembly having a configuration as shown in Figure 25. Burst tests were conducted as described below.

a. Ring Assembly No. 1 - Tested at 70°F

After proof test (475 psig), the diffusion bonded joint was leak tight when inspected with a helium leak detector. When hydrostatically burst tested at room temperature, the tank failed at 550 psig. This pressure corresponds to a hoop tensile stress of 23,000 psi and a joint shear load of approximately 1130 pounds per inch. The diffusion bonded joint failed in shear as shown in Figure 27. The failure appeared to originate where incomplete bonding occurred because of the misalignment of the assembly as previously discussed.

b. Ring Assembly No. 3 - Tested at -320°F

When pressurized with liquid nitrogen, (-320°F), this tank failed at 1440 psig. This failure load corresponds to a hoop tensile stress of 62,000 psi and a joint shear load of 3100 pounds per inch. The tank failed in the longitudinal weld of the 2219-T62 tank shell as shown in the photograph on Figure 28. The failure then propagated into the aluminum ring in the bonded joint and peeled the aluminum ring from the stainless steel ring. The peeling occurred at the diffusion zone between the silver plating and 2219 aluminum alloy. Inspection of the peeled joint showed that 100% of the surface was diffusion bonded.

Based upon the results of the eight-inch diameter test assembly investigation, in conjunction with the development work on flat specimens, the diffusion bonding process was selected as the method for fabrication of the 20-inch diameter tanks. As mentioned previously, the fusion welding method was considered to be difficult for adaptation to production conditions, due to requirements for manual aluminizing and welding techniques. In addition, the fusion welding process did not provide any significant growth potential in obtaining higher tank hoop tensile stresses.

Diffusion bonding resulted in high strength, ductile joints without formation of detrimental intermediate phases at the joint interface. Due to the lower processing temperature, as compared to fusion welding, diffusion bonding inherently retains higher base metal properties. In addition, adaptability of the diffusion bonding process to production use appeared excellent. Process controls such as cleaning, assembling and thermal cycling, were readily compatible with present production technology and facilities. Modifications of the tooling method development could be effectively used for economical fabrication of large tubular assemblies.

TWENTY-INCH DIAMETER TEST ASSEMBLIES

Four 20-inch diameter 321 stainless steel to 2219 aluminum alloy joint assemblies were fabricated by diffusion bonding. Figure 29 shows the configuration of the test tank containing a diffusion bonded ring assembly. Figure 30 shows the arrangement of the ring assembly and of the differential thermal expansion fixture used for diffusion bonding.

This portion of the report will be discussed in three main sections:

1. Description of Parts for 20-Inch Diameter Assemblies
2. Diffusion Bonding of 20-Inch Diameter Ring Assemblies
3. Pressure Testing of 20-Inch Diameter Tanks

DESCRIPTION OF PARTS FOR 20-INCH DIAMETER ASSEMBLIES

321 STAINLESS STEEL RINGS

Rings of 321 stainless steel 11 inches long were cut from a section of an experimental Saturn cold-spun fuel line tube which had a yield strength of approximately 140,000 psi. Diameter and wall thickness measurements of the machined rings are listed in Table V.

2219 ALUMINUM ALLOY RINGS

A cylindrical shell of 2219 aluminum alloy was made by rolling and butt fusion welding 0.500-inch thick plate. After welding, the shell was solution treated and aged to the -T62 condition. Following heat treatment, three-inch-long rings were machined to the dimensions shown in Table V.

ALUMINUM TANK SHELLS

Tank shells of 2219 aluminum alloy were rolled, welded and heat treated to the -T62 condition. The shells were 9.00-inches long and had an I.D. of 20.00 inches and a wall thickness of 0.125 inch.

TANK HEADS

Flat tank heads of 2219-T62 aluminum alloy and annealed 321 stainless steel were machined from 1.50-inch thick plate.

DIFFUSION BONDING OF 20-INCH DIAMETER RING ASSEMBLIES

The 321 stainless steel and 2219 aluminum alloy rings were silver plated on the interface surfaces, as shown in Figure 31. The plating procedures used are outlined in the Appendix C. Immediately prior to bonding, the silver plated surfaces were lightly abrasively cleaned with 240 grit sand paper and cleaned with acetone. Prior to assembly, the tooling used for diffusion bonding was vapor degreased.

The following sequence was used to assemble, diffusion bond, and disassemble the parts. All of the major tooling and assembly components are illustrated in Figure 30. Each assembly sequence discussed below, i.e., items 1 through 5, is also designated on Figure 30, such as "(1)".

1. The stainless steel tube was heated to 250°F and was installed with a shrink fit on the 321 stainless steel inner mandrel. See Table V for shrink fit tolerances.

2. The inner spacer, base plate, bolt and nut were installed to the stainless steel ring and mandrel.

3. The outer spacers were attached to the stainless steel ring.

4. The aluminum ring was heated to 250°F and installed (shrink fit) over the stainless steel ring and bearing against the outer spacers. After installing on the stainless steel ring, the aluminum ring had an interference fit of approximately 0.025 inches with the outer tool ring. This 0.025-inch interference fit provided the required preload to produce adequate pressure during bonding.

5. The outer "T-1" low alloy steel ring was preheated to 600°F for installation onto the aluminum ring. Liquid nitrogen (LN_2) was poured on top of the mandrel to shrink the aluminum ring assembly. The aluminum ring assembly was then lowered into the heated tool ring as shown in Figure 32.

6. The entire diffusion bond assembly and fixture were held at room temperature in an air atmosphere for 40 minutes until all parts stabilized at approximately 250°F. The fixture and assembly were then placed in an air atmosphere furnace for diffusion bonding at the desired time and temperature. After diffusion bonding, the assemblies were removed from the furnace and air cooled.

7. After cooling, the diffusion bonded assembly was removed as shown in Figure 33. LN_2 was poured on top of the inner mandrel, while the outer tool ring was maintained near room temperature by heating with an oxyacetylene torch. When the inner mandrel cools sufficiently, the outer tool ring dropped from the assembly. This operation required approximately 30 minutes and about 10 gallons of LN_2.

8. The base plate and spacers were removed and the diffusion bonded assembly was heated with an oxyacetylene torch as shown in Figure 34. When the diffusion bonded ring assembly reached room temperature, it slid from the mandrel as shown in Figure 35. Time required for this operation was approximately three minutes.

The following describes the diffusion bonding cycle, examination, and thermal shock cycling results for each ring assembly:

RING ASSEMBLY NO. 1

The first ring assembly was diffusion bonded at 500°F for 4 hours. This bonding cycle was selected for the following reasons: (1) analysis indicated that the 20-inch diameter tooling would provide greater differential expansion than the 8-inch diameter tooling, (2) the lowest possible time and temperature cycle was desirable in order to minimize degradation of the 2219 aluminum alloy properties, and (3) the parameter study showed that the 500°F for 4 hour cycle produced the most ductile joint.

After bonding, measurements showed that the aluminum ring had compressively yielded 0.003 to 0.004-inch in wall thickness. The stainless steel ring was reduced by approximately 0.008-inch in diameter as shown in Table VI. This indicates that compressive residual stresses were retained in the 321 stainless steel ring. Measurements of the tooling after bonding (Table V) showed the inner mandrel was reduced 0.004-inch in diameter due to shrinkage.

The bonded assembly was then thermally cycled ten times from RT to -320°F with no evidence of joint failure.

RING ASSEMBLY NO. 2

The second ring assembly was also diffusion bonded at 500°F for 4 hours. After bonding, measurements showed the aluminum ring had compressively yielded 0.001 to 0.002-inch in wall thickness and the stainless steel ring was reduced by approximately 0.008-inch in diameter as shown in Table VI. Measurement of the tooling (Table V) showed the inner mandrel contracted an additional 0.004-inch in diameter. Therefore, a total of 0.008-inch in shrinkage had occurred after processing of assemblies No. 1 and 2. Thermal cycling ten times from RT to -320°F resulted in no evidence of joint failure.

RING ASSEMBLY NO. 3

Prior to diffusion bonding the third assembly, the outside diameter of the inner mandrel was increased to 20.000-inch (Table V). This was accomplished by shrink-fitting a stainless steel hoop, having an 0.005-inch wall, around the periphery of the inner mandrel.

The third assembly was diffusion bonded at 500°F for 4 hours. After bonding, measurements showed that the aluminum ring had compressively yielded 0.003 to 0.004-inch in wall thickness and that the stainless steel ring contracted approximately 0.008-inch in diameter (Table VI).

No evidence of joint failure was observed in the bonded assembly after thermally cycling ten times from RT to -320°F.

RING ASSEMBLY NO. 4

Measurements of diffusion bonded assemblies No. 2 and 3, revealed that the amount of compressive yielding obtained on the aluminum ring was marginal to produce 100% diffusion bonded joints. It was evident that the 500°F for 4 hour cycle did not result in uniform and sufficient pressure on the joint interface with the 20-inch diameter tooling. Therefore, the fourth ring assembly was diffusion bonded at 600°F for 2 hours. This thermal cycle allowed more uniform and higher bonding pressure and provided additional compressive yielding of the aluminum.

After bonding, measurements showed the aluminum had compressively yielded 0.006 to 0.007-inch in wall thickness. The diameter of the 321 stainless steel ring was reduced by approximately 0.008-inch, (Table VI).

The bonded assembly was then thermally cycled ten times from RT to -320°F with no evidence of joint failure.

PRESSURE TESTING OF 20-INCH DIAMETER TANKS

Each of the four diffusion bonded ring assemblies was welded into a tank assembly as shown in Figure 29. Each tank was leak tested with a helium leak detector. The diffusion bonded joints of Tank Nos. 1, 3 and 4 were found to be leak tight. Tank No. 2 exhibited a small leak in the diffusion bonded joint.

After the helium leak check, each tank was pressure cycled and burst tested at the pressures and temperatures shown in Table VII. The following describes the results of the pressure testing:

TEST ASSEMBLY NO. 1

The first tank successfully passed the room temperature cycling test (Table VII). During the burst test at room temperature, the tank failed at 470 psig. The tank failed by shearing in the diffusion bonded joint as illustrated in Figure 36. Inspection of the joint showed the failure occurred by shearing partly at the silver-aluminum interface (40%) and partly at the silver-silver interface (60%). Measurements of the tank after testing showed the aluminum ring had deformed 0.070 inches radially as shown in Table VII and that the stainless steel ring had returned to its original diameter of 20.161 inches.

The appearance of the joint after testing indicated the bonded area was void free. As noted previously, however, the aluminum ring deformed during the burst test as shown by Table VII. This deformation would apply a peel force to the bonded area and contribute to initiation of the fracture.

TEST ASSEMBLY NO. 2

The second tank, tested with LN_2, burst at 350 psig during the 82nd cycle of the cycling test. The joint failed primarily by shear at the silver-silver interface. Examination of the joint revealed that the fracture occurred in the area where the helium leak-check indicated a small leak. The joint was bonded randomly in only 25% of this area.

Measurements of the tank after testing showed the aluminum ring had not deformed during cyclic pressure testing, and that the stainless steel ring had returned to its original diameter of 20.162 inches.

The cause of the tank failure was incomplete diffusion bonding. Table VI shows the aluminum ring compressively yielded from 0.001 - 0.003-inch during bonding. This amount of deformation was not sufficient to bring all areas of the joint into the intimate contact which is required for complete diffusion bonding of the faying surface. Previous parameter work indicated that a minimum of 0.004-inch of compressive yielding of the aluminum alloy was necessary to insure a strong void-free joint. Therefore, due to the shrinkage of the inner mandrel during the fabrication of assemblies No. 1 and 2, it was evident that sufficient pressure was not obtained on assembly No. 2 to obtain the desired compressive yielding of the aluminum ring.

TEST ASSEMBLY NO. 3

The third tank successfully passed the cycling test when pressurized with LN_2, Table VII. During the burst test with LN_2 the tank failed at 505 psig. by shearing partly at the silver-silver (70%) and partly at silver-aluminum (30%) interfaces. Examination of the joint indicated that it contained approximately 10% unbonded area randomly distributed. Measurements of the tank showed the aluminum ring had deformed 0.05-inch radially (Table VII) during burst testing and that the stainless steel ring had returned to its original diameter of 20.162 inches.

Table V shows that the aluminum ring had only compressively yielded 0.003-0.004-inch in wall thickness.

The excessive deformation of the aluminum ring during burst testing applied a peeling force to the bonded area which contributed to initiation of the failure.

TEST ASSEMBLY NO. 4

Based upon the cumulative processing experience obtained from the first three 20-inch diameter assemblies, the fourth tank assembly was made and it produced the most successful results.

This assembly successfully passed the -320°F cyclic test (310 psig for 60 cycles, and 240 psig for 140 cycles) as shown in Table VII. The tank burst at 670 psig during testing. This burst pressure is equivalent to a hoop stress of 53,600 psi which exceeds the yield strength of 2219-T62 aluminum alloy at -320°F.

The joint sheared primarily at the silver-aluminum interface as illustrated in Figure 36. Examination of the joint showed the faying surface had been completely diffusion bonded. Measurements of the tank revealed the aluminum ring had deformed 0.110-inch radially (Table VII) during burst testing and that the stainless steel ring had returned to its original diameter of 20.161 inches.

Table VI shows the aluminum ring compressively yielded 0.006-0.007-inch in wall thickness during diffusion bonding. This demonstrates that the 600°F for 2 hours diffusion bonding cycle exerted adequate pressure during bonding and brought the faying surfaces into complete contact.

The 0.110-inch radial deformation of the aluminum ring during burst test, Table VII, applied a peel load to the bonded area which probably initiated failure of the joint.

Excessive deformation of the 2219 aluminum alloy ring had also occurred during burst testing assemblies Nos. 1 and 3. Redesign of the aluminum ring to provide an increase in wall thickness of 15 per cent, will significantly decrease this peel load and result in higher burst pressures.

DISCUSSION

This investigation has considered the problem of obtaining a structurally reliable joint between stainless steel and 2219 aluminum alloy tubing of large diameter. The program results show that diffusion bonding is the best process to produce these joints. A simple, reliable and potentially economical process for diffusion bonding has been developed and demonstrated. Two other feasible processes - brazing and GTA welding - which have been analyzed or tested during the course of this investigation have been shown to have inherent disadvantages or limitations when applied to the problem at hand.

The GTA fusion welding process could be adapted for directly joining large diameter tubing of 2219 aluminum alloy to 321 stainless steel. However, the method will not produce reliable joints due to (1) the difficulty in controlling the amount of brittle interfacial iron-aluminide phase, (2) the resultant low joint peel strength and (3) the need for manual aluminizing and welding operations.

The dip brazing method was not developed further in this program because (1) limiting the inherent formation of embrittling phases at the joint interface would be difficult; (2) 2219 aluminum alloy cannot be brazed directly to stainless steel and therefore, a lower strength transition material such as 6061 aluminum alloy would be required; and (3) tooling and tolerance requirements would severely limit its use in joining large diameter components.

In contrast, the diffusion bonding process overcame the major problem common to the other two processes. The low process temperature combined with the use of diffusion aids ensured effective control of intermetallic compound development. In addition, extremely close tolerance control of time and temperature was not required to produce reliable joints by this process. However, in the case of the third parameter pressure, a precise method had to be devised to apply the correct bonding force to the tubular assembly. Such a method would ensure application of sufficient uniform force to the mating surfaces to provide complete bonding, yet not apply so much force that excessive compressive yielding of the aluminum component would result in deformation of the bonded joint. By taking advantage of the difference between the thermal expansion coefficients of low alloy steel and stainless steel, tooling was developed which provided a uniform and reproducible bonding pressure. This investigation has also shown that proof of adequate pressure application can be readily ascertained by measuring joint thickness prior to and after bonding. Since adequate compressive yielding of the aluminum alloy during bonding gives assurance of a 100% bonded joint, the measurement of joint thickness provides a simple and unique method of process control.

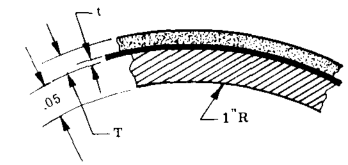
The diffusion bonding process parameters of time, temperature, and pressure have been sufficiently investigated to define a production process resulting in consistent joint properties.

The process variables of surface finish, cleaning, and plating were less critical than the requirement for uniform and consistent application of pressure. Surface finish, either as machined or cold spun, resulted in producing acceptable bonded joints. Cleaning of the joint interfaces prior to bonding was required. However, once cleaned, the silver plated surfaces, even when exposed to normal shop soil and furnace oxidation, provided successful diffusion bonds. Commercial practices for silver plating aluminum and stainless steel are adequate. The dimensional control of parts and tooling, while critical in some respects, is not beyond current machine shop practice.

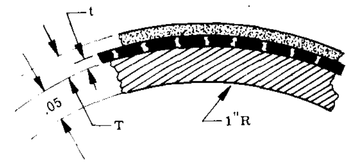
The results of corrosion testing indicate that either protective finishes or a controlled low humidity environment are necessary. The protection required would be similar to that required for any joint consisting of stainless steel to aluminum alloy.

TABLE 1 SUMMARY OF STEEL PRECOAT DEVELOPMENT TYPE 321 STEEL

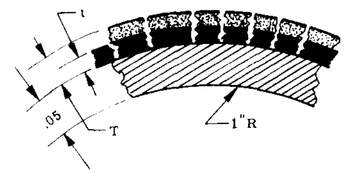
SPECIMEN NUMBER	MOUNT NUMBER	TYPE PLATING (1)	ALUMINUM COATING: ALLOY	ALUMINUM COATING: APPLICATION METHOD	DIFFUSION PROCESS: HEAT SOURCE	DIFFUSION PROCESS: TIME	DIFFUSION PROCESS: TEMP. °F	DIFFUSION PROCESS: FLUX	QUALITY OF ALUMINIZED SURFACE: SURFACE APPEARANCE	TOTAL THICKNESS T - INCHES	DIFFUSED LAYER THICKNESS t - INCHES	TYPE MICRO APPEARANCE	REFERENCE FIGURE NUMBER
2	43550	SILVER	1100	PLASMA ARC SPRAY .003"/.004" THICK	MOLTEN BRAZING SALT (FLUX)	5 MIN.	1105	PARK "E"	SMOOTH	.0008	.0003	3	
18	●	TIN	1100						ALUMINUM FLOWED FROM STEEL			●	
34	43552	ZINC	1100						ROUGH	.0009	.0005	3	
49	43552	COPPER	1100						SMOOTH	.0017	.0017	3	
68	●	BARE	1100						STEEL DID NOT WET			●	
1	4356	SILVER	718			1 MIN.	1150	PARK "E"	SMOOTH	.001	.0002	1	
1R	4357	SILVER	1100						SMOOTH	.002	.0006	2	
19	4356	TIN	718						SMOOTH	.001	.0002	2	
19R	4357	TIN	1100						SMOOTH	.0012	.0006	2	
33	4356	ZINC	718						ROUGH	.0008	.0005	3	
33R	4357	ZINC	1100						ROUGH	.001	.0005	3	
51	4356	COPPER	718						SMOOTH	.0012	.0003	3	
51R	4357	COPPER	1100						SMOOTH	.003	.003	3	6A
67	●	BARE	718						STEEL DID NOT WET			●	
67R	●	BARE	1100						STEEL DID NOT WET			●	
4	4358	SILVER	1100	PLASMA ARC SPRAY .003"/.004" THICK	RADIANT HEAT IN AIR	30 SEC.	(2)	ALCOA 33	SMOOTH	.006	.0002	2	6B
20	4358	TIN	1100						SMOOTH	.002	.0002	2	
35	4358	ZINC	1100						ROUGH	.0025	.001	2	
50	●	COPPER	1100						STEEL DID NOT WET			●	
66	●	BARE	1100						STEEL DID NOT WET			●	
69	4358	BARE	718 WIRE	ALUMINUM APPLIED MANUALLY				JENSEN 227	SMOOTH	.004	.00015	1	5
13	43583	SILVER	718 POWDER					ALCOA 33	SMOOTH & POROUS	.005	.0002	1	
72	44720	BARE	718 WIRE			3 MIN.		JENSEN 227	SMOOTH	.004	.002	3	
73	44720	BARE	718 WIRE			30 SEC.		JENSEN 227	SMOOTH	.0035	.00015	1	
3	4401	SILVER	718	PLASMA ARC SPRAY .003"/.004" THICK	FURNACE WITH ARGON ATMOSPHERE	1 MIN AT TEMP.	1090	ALCOA 33	UNEVEN	.0008	.0002	2	
3R	4401	SILVER	1100						SMOOTH	.0008	.0008	3	
17	●	TIN	718						ALUMINUM FLOWED FROM STEEL			●	
17R	4401	TIN	1100						SMOOTH	.0016	.0014	3	
36	●	ZINC	718						UNACCEPTABLE - BLACK COATING ON STEEL			●	
36R	●	ZINC	1100									●	
52	4401	COPPER	718						SMOOTH	.0025	.0004	3	
52R	●	COPPER	1100						STEEL DID NOT WET			●	
65	4401	BARE	718						SMOOTH	.0016	.0014	3	
65R	●	BARE	1100						STEEL DID NOT WET			●	
7	●	SILVER	718			1 MIN AT TEMP.	1000		STEEL DID NOT WET			●	
25	44260	TIN	718						ALUMINUM FLOWED FROM STEEL			●	
27	44260	TIN	1100						ROUGH	.001	.0003	3	
41	44260	ZINC	718						SMOOTH	.001	.001	3	
43	44260	ZINC	1100						SMOOTH	.001	.0008	3	
15	44260	SILVER	1100	DIP IN FLUX COVERED MOLTEN ALUMINUM (3)		15 SEC.	1325	(3)	SMOOTH	.0009	.0004	3	
29	44260	TIN	1100						SMOOTH	.001	.0005	3	
45	4400	ZINC	1100						SMOOTH	.0008	.0003	3	
56	4400	COPPER	1100						SMOOTH	.0007	.0003	3	
74	4400	BARE	1100						SMOOTH	.0008	.0004	3	4



TYPE 1 - THIN DIFFUSION ZONE NO CRACKS



TYPE 2 - MEDIUM DIFFUSION ZONE SOME CRACKING



TYPE 3 - HEAVY DIFFUSION ZONE CRACKS TO SURFACE

(1) PLATING THICKNESS - .0007"

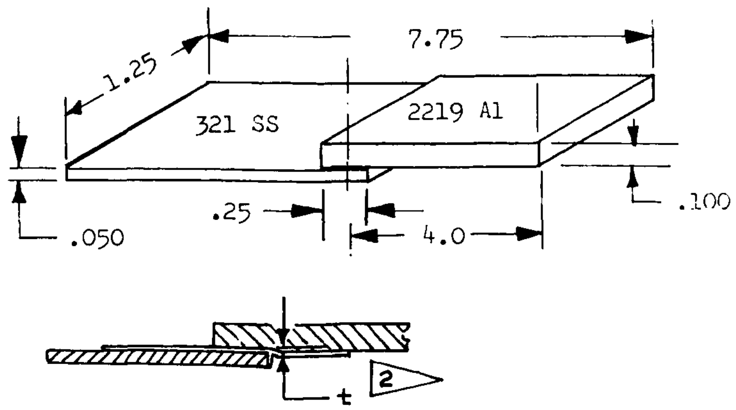
(2) SPECIMEN HELD AT TEMPERATURE WHER ALUMINUM WOULD MELT AND FLOW

(3) MOLTEN ALUMINUM COVERED WITH:
5 PARTS A1-DIP CS 217 SALT
1 PART PARK EAF-196 CONCENTRATE

TABLE II

SUMMARY OF DIFFUSION BONDING DEVELOPMENT
2219 ALUMINUM TO 321 STEEL

Test No.	Specimen Surface Preparation [1]	Bonding Temp. °F	Bonding Pressure psi	Bonding Time Hours	Amount of [2] Compressive Yielding t-Inches	Shear Strength psi	Appearance of Metallurgical Control Specimen at the Original Joint Interface
1	Bare	600	21,400	4.0	.035	1730	Slight diffusion Bonding
2	Bare	600	21,400	1.5	.030	450	
3	Copper plate	500	25,400	3.0	.003	Peel Tested Only	Almost complete Solid state diffusion
4	Copper plate	500	20,000	3.0	.000		
5	Silver plate per Appendix B	600	17,000	1.25	0	Not Tested	Intermittent Solid state diffusion
6	Silver plate per Appendix B	600	21,400	1.50	.014	7,750	Complete solid state diffusion
7		600	21,400	1.50	.014	8,370	
8	Silver plate per Appendix B	500	20,000	3.0	0	9,550	Intermittent Solid state diffusion
9	Silver plate per Appendix B	500	22,500	4.0	.002	9,309	Intermittent Solid state diffusion
10	Silver plate per Appendix B	500 500	26,000 26,000	3.5 4.5	.003 .005	12,800 12,900	Complete solid state diffusion
11	Silver plate per Appendix C	500	26,000	4.0	.004	14,200	Complete solid state diffusion
12	Silver plate per Appendix C	600	20,000	2.0	.006	12,600	Complete solid state diffusion



[1] Prior to bonding, specimens were abrasively cleaned and wiped with acetone.

TABLE III
SUMMARY OF MECHANICAL TEST RESULTS
Shear Stress-psi

Specimen No.	Type Specimen	77°F	-320°F	-423°F
1	Welded	16,800		
2	Single	18,040		
3	Lap	18,000		
4	2		16,330	
5			17,170	
6			16,330	
7				15,800
8				17,400
9				19,000
10	Welded	16,640		
11	Double	16,480		
12	Lap	15,920		
13	2		20,160	
14			21,120	
15			15,910	
16				19,100
17				23,100
18				19,500
19	3 *Diffusion Bonded	17,690		
20	Single Lap	16,410		
21		15,800		
22	Plated per		19,000	
23	Appendix B		18,310	
24			23,250	
25				19,900
26				20,930
27				16,250
28	3 *Diffusion Bonded	14,500		
29	Double Lap	15,880		
30		14,280		
31	Plated per		15,750	
32	Appendix B		18,550 1	
33			20,900 1	
34				20,450
35				20,600
36				24,000
37	3 *Diffusion Bonded	14,600		
38	Single Lap	17,200		
39	Plated per	15,100		
40	Appendix C			18,800
41				21,000
42				23,750

1 Specimens broke in grip section

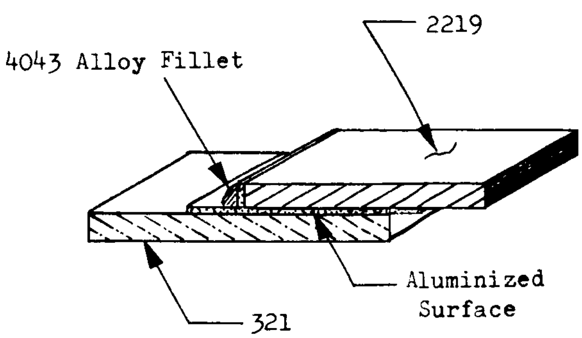
2 Stress calculation based on throat dimension of fillet weld.

3 All Diffusion Bonded Specimens Bonded at 600°F - 2 Hours

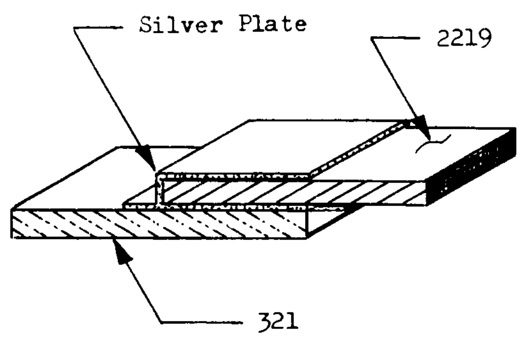
TABLE IV

SUMMARY OF CORROSION TESTS OF 321 STAINLESS STEEL JOINED TO 2219 ALUMINUM ALLOY

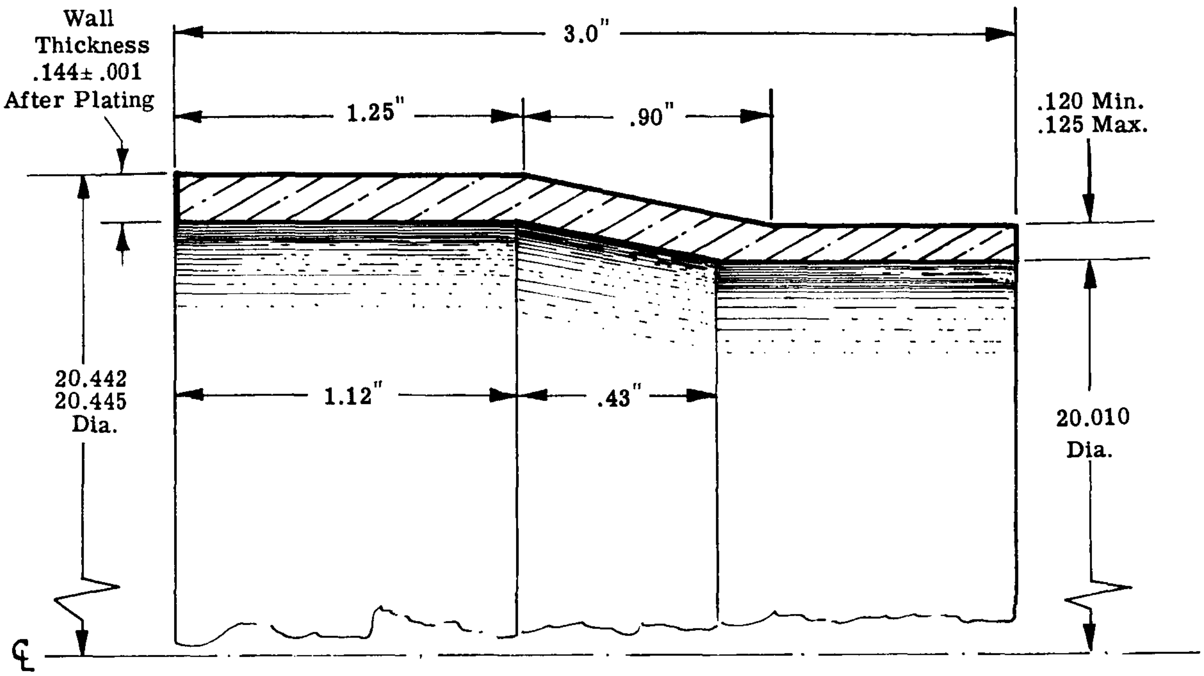
Specimen Configuration	Specimen Precoat Method	Number of Specimens per Test Solution				
		5% NaCl Spray				Tap Water + 0.1% NaCl
		72 hours	144 hours	360 hours	Tap Water 14 days	14 days
Fillet Weld Lap Joint	Steel Dipped in Molten 1100 Alloy	1	1	1		
Fillet Weld Lap Joint	Steel Manually Coated with 718 Alloy	1	1	1	2	2
Fillet Weld Lap Joint	Silver Plated Steel Manually Coated with 718 Alloy	1	1	1		
Diffusion Bond Lap Joint	Silver Plate on Steel and on Aluminum	1	1	1	2	2



Welded Specimen



Diffusion Bonded Specimen



SECTION VIEW OF 2219 ALUMINUM RING

PART	DIMENSION	DIFFUSION BONDED ASSEMBLY NUMBER			
		No. 1	No. 2	No. 3	No. 4
STAINLESS STEEL MANDREL	OUTSIDE DIA. [1]	19.998	19.994	20.000	20.000
T-1 STEEL RING	INSIDE DIAMETER	20.422	20.422	20.421 20.423	20.421 20.423
STAINLESS STEEL RING (After Plating)	OUTSIDE DIA.	20.161	20.162	20.162	20.161
	WALL THICKNESS	.084 -.085	.084 -.085	.084 -.085	.083-.084
2219 ALUMINUM RING (After Plating)	OUTSIDE DIA	20.445	20.445	20.443	20.442
	WALL THICKNESS	.144 -.145	.144 -.145	.143-.144	.143

[1] After Assembly No. 2 the Mandrel Diameter Was 19.990"

TABLE V

DIMENSIONS OF PARTS PRIOR TO DIFFUSION BONDING

DIMENSION	DIFFUSION BONDED ASSEMBLY NUMBER			
	NO. 1	No. 2	NO. 3	NO. 4
Decrease in Wall Thickness of Aluminum Ring	.003-.004	.001-.003	.003-.004	.006-.007
Outside Diameter of Stainless Steel Ring	20.153	20.154	20.154	20.152
Decrease in Diameter of Stainless Steel Ring	0.008	0.008	0.008	0.008

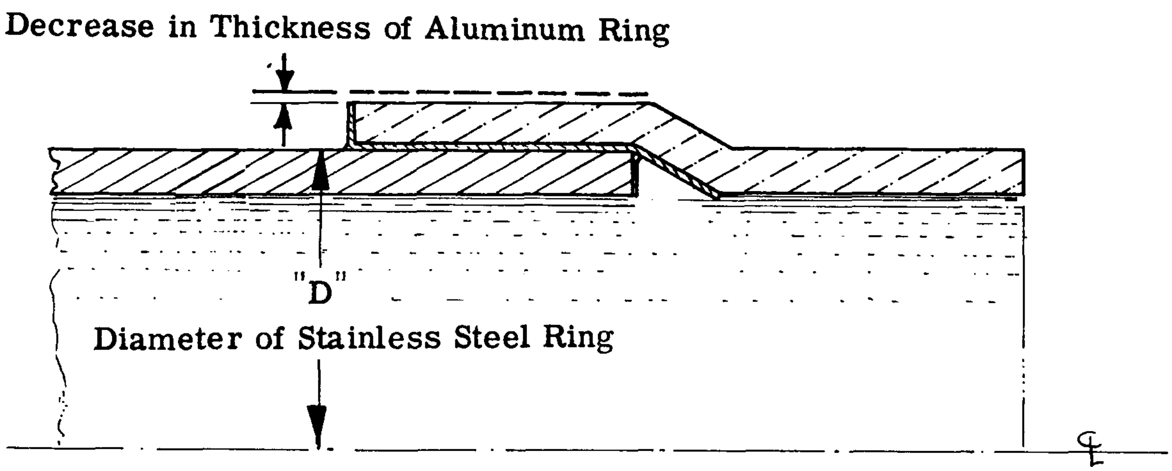


TABLE VI

MEASUREMENTS OF RING ASSEMBLY AFTER DIFFUSION BONDING

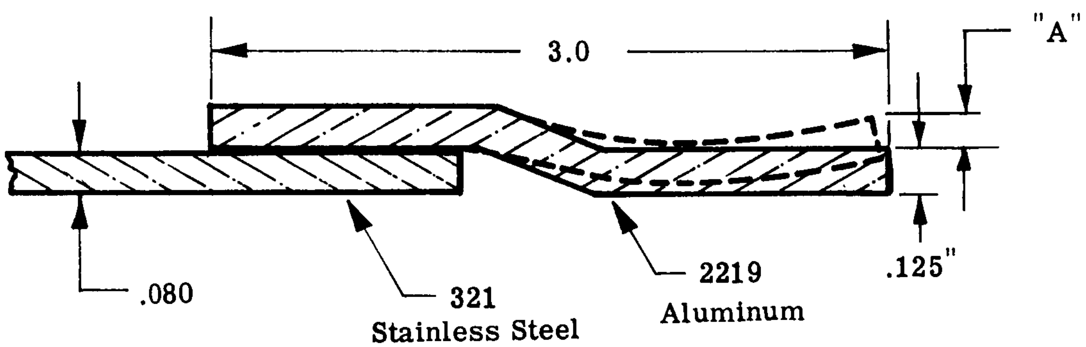
TABLE VII

SUMMARY OF 20 - INCH DIAMETER TANK TESTS

TANK NO.	TEST METHOD	CYCLE PRESS PSIG	NUMBER CYCLES	BURST PRESSURE PSIG	$\frac{Pr}{t}$ PSI [1]	DEFORMATION OF ALUMINUM "A" - INCHES
1	WATER AT R.T.	350	200	470	37,600	.070
2	LN_2 -320°F	350	85 (Failed)	-	28,000	0
3	LN_2 -320°F	350	92 [2]	505	40,400	.050
4	LN_2 -320°F.	310 240	60 140	670	53,600	.110

[1] Based on .125" Aluminum Wall Thickness

[2] Cycling Pump Failed on 92nd Cycle



DEFORMATION OF ALUMINUM RING DURING BURST TEST

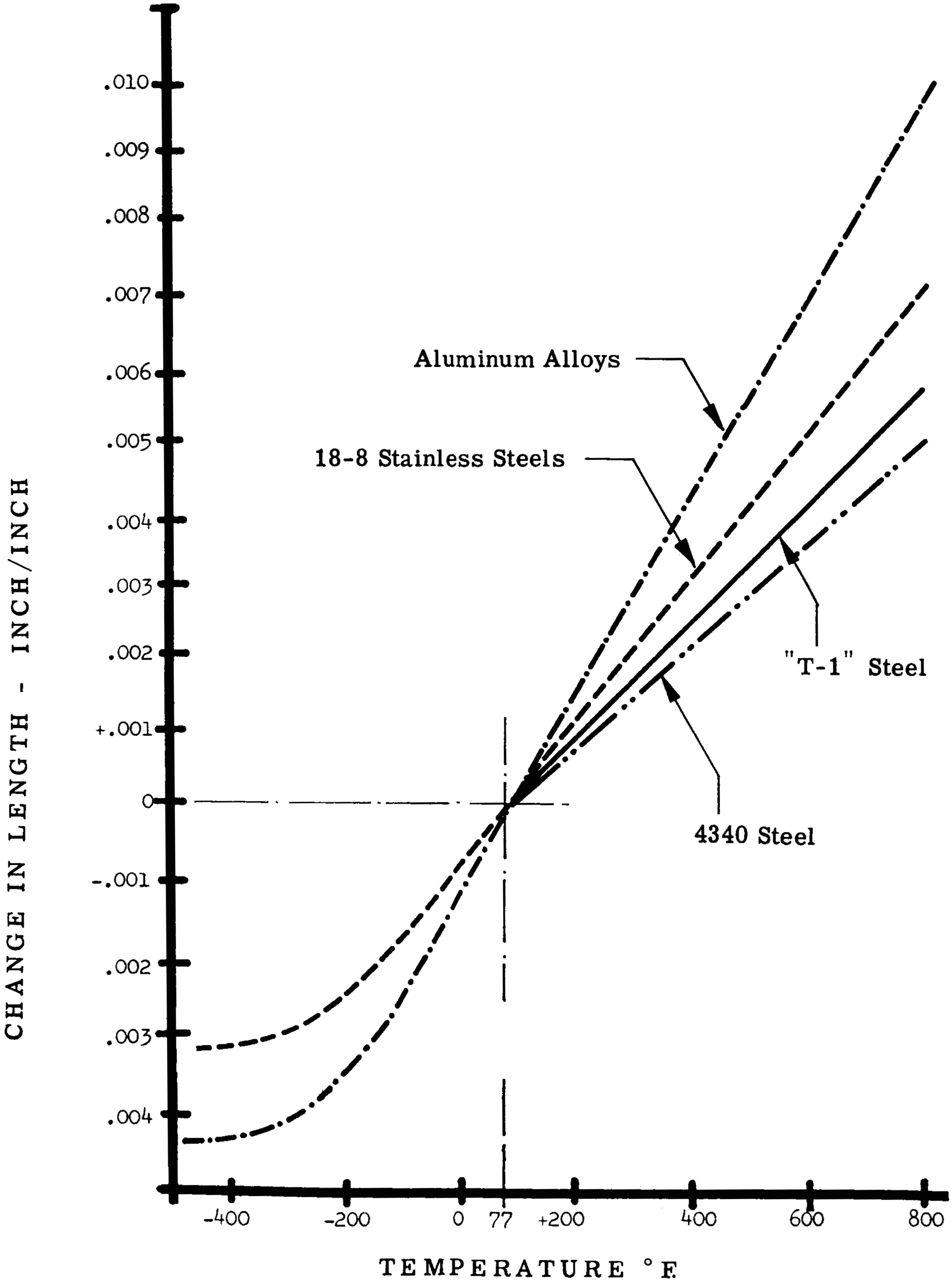
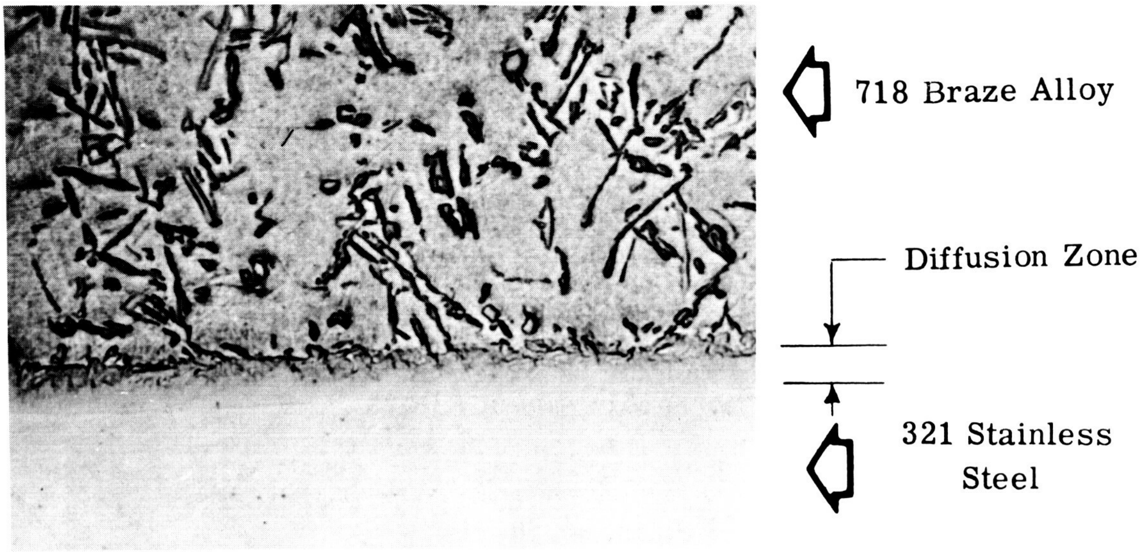


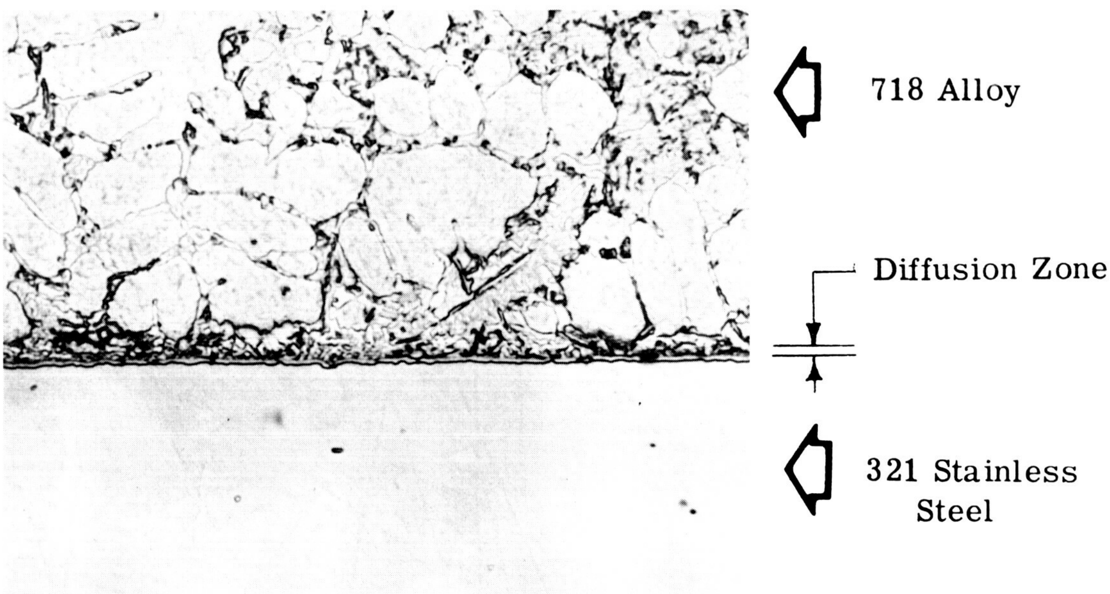
FIGURE 1:

COMPARISON OF THERMAL EXPANSION OF VARIOUS ALLOYS



A Dilute Kellers Etch 250X

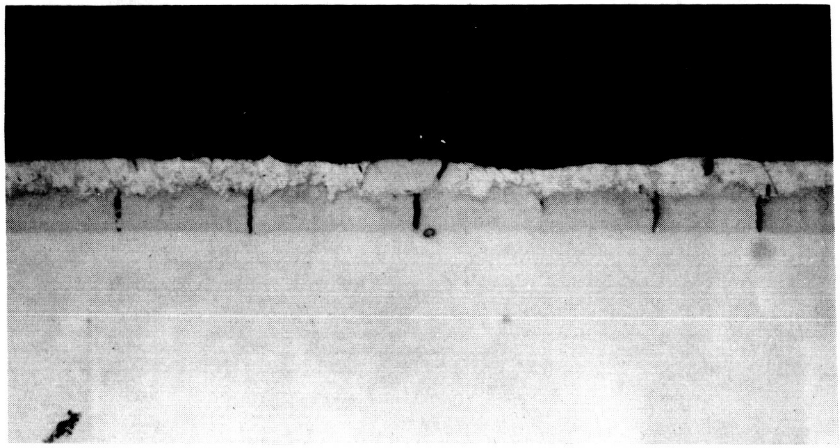
718 Braze Alloy On Aluminized (1100) 321 Stainless Steel



B Dilute Kellers Etch 250X

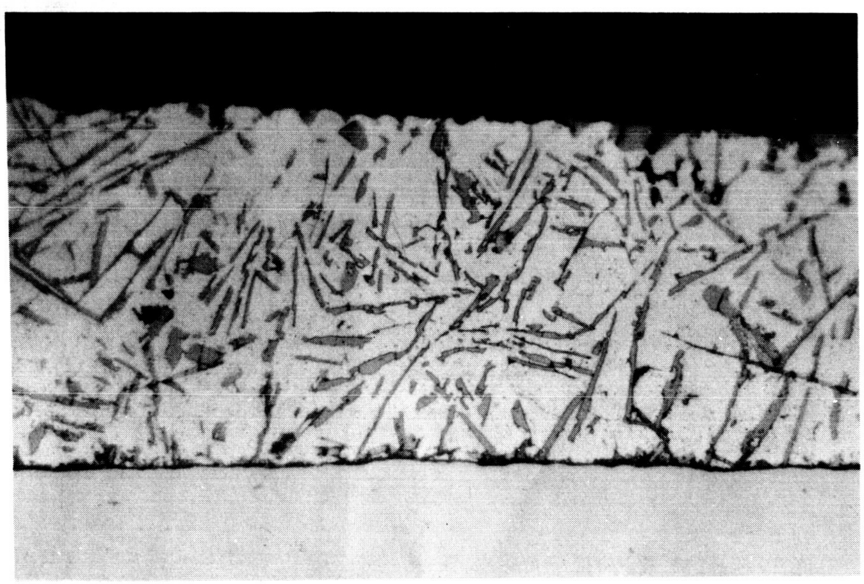
718 Braze Alloy on Copper Plated 321 Stainless Steel

FIGURE 3: PHOTOMICROGRAPHS SHOWING DIFFUSION ZONE ON ALUMINUM BRAZED 321 STAINLESS STEEL



Dilute Kellers Etch 500X

FIGURE 4 ALUMINIZED COATING - AFTER 1-INCH RADIUS BEND COATING APPLIED BY DIPPING BARE 321 STEEL IN MOLTEN 1100 ALLOY ALUMINUM (1325°F-15 SEC.)



1/2% HF Etch 500X

FIGURE 5 ALUMINIZED COATING - AFTER 1-INCH RADIUS BEND COATING OF 718 ALLOY APPLIED MANUALLY, DIFFUSED BY RADIANT HEAT FOR 30 SECONDS

1/2 % HF Etch 350X

A COPPER PREPLATE - 1100 ALLOY, PLASMA ARC SPRAYED
DIFFUSED IN 1150°F SALT FOR 1 MINUTE

1/2% HF Etch 500X

B SILVER PREPLATE - 1100 ALLOY, PLASMA ARC SPRAYED
DIFFUSED IN 1150°F SALT FOR 1 MINUTE

FIGURE 6 ALUMINIZED COATING - AFTER 1-INCH RADIUS BEND TYPICAL OF COPPER AND SILVER PREPLATE

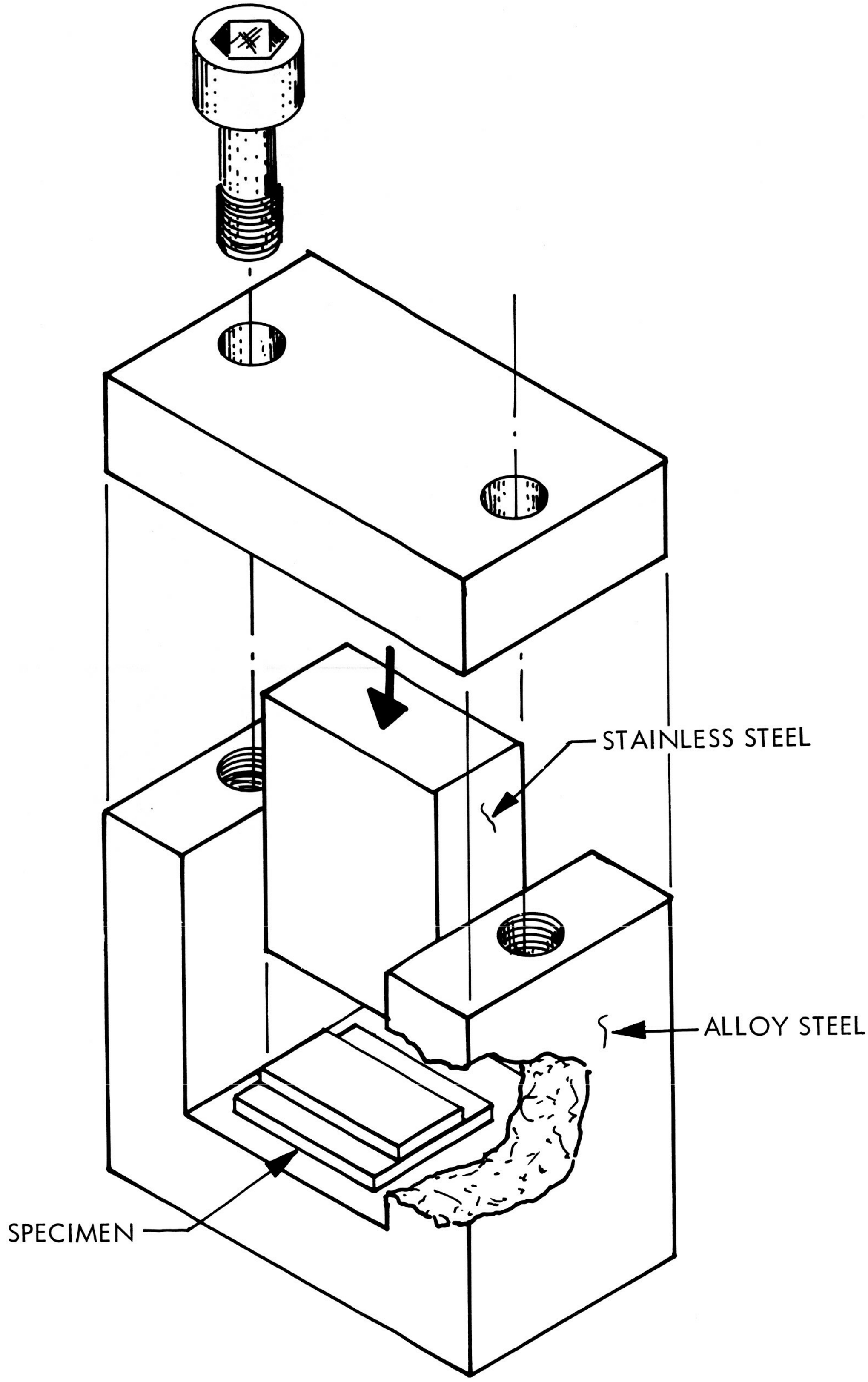
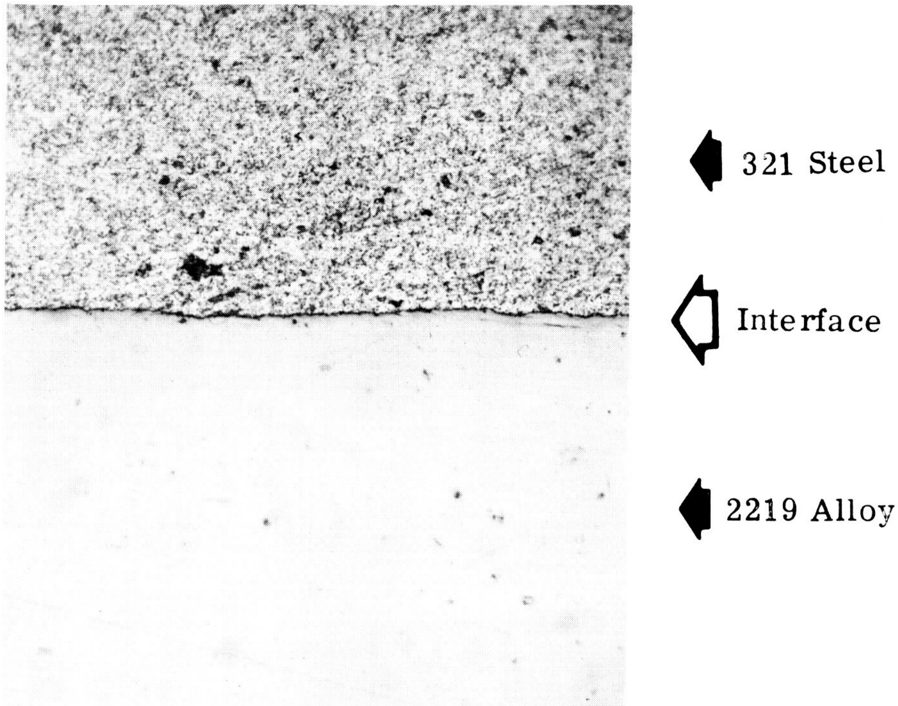


FIGURE 8: DIFFERENTIAL THERMAL EXPANSION PRESS

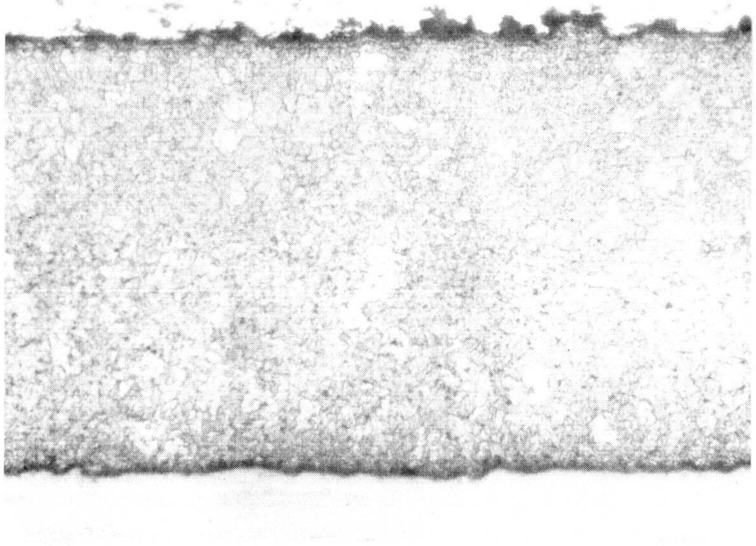


Dilute Keller's Etch 500X

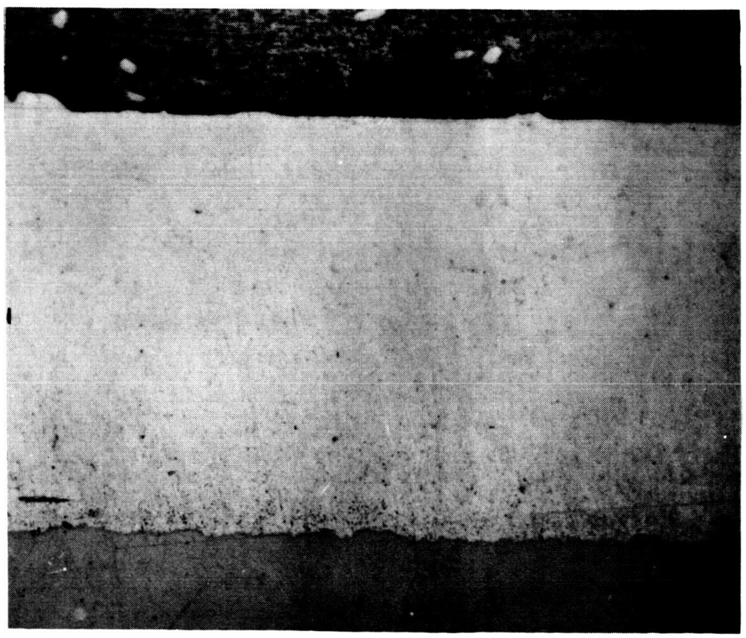
Bonding Temperature - 700°F - 20 Minutes

Bonding pressure initially 15000 psi, which was increased at 700°F to reduce the aluminum thickness by 25%.

FIGURE 9 DIFFUSION BONDED BARE 321 STAINLESS STEEL TO BARE 2219 ALUMINUM ALLOY



A Dichromate Etch



B 1/2% HF Etch

FIGURE 10 DIFFUSION BONDED 2219 ALUMINUM TO 321 STEEL
3.5 HOURS AT 500°F AND 26,000 PSI PRESSURE
BOTH ALLOYS SILVER PLATED

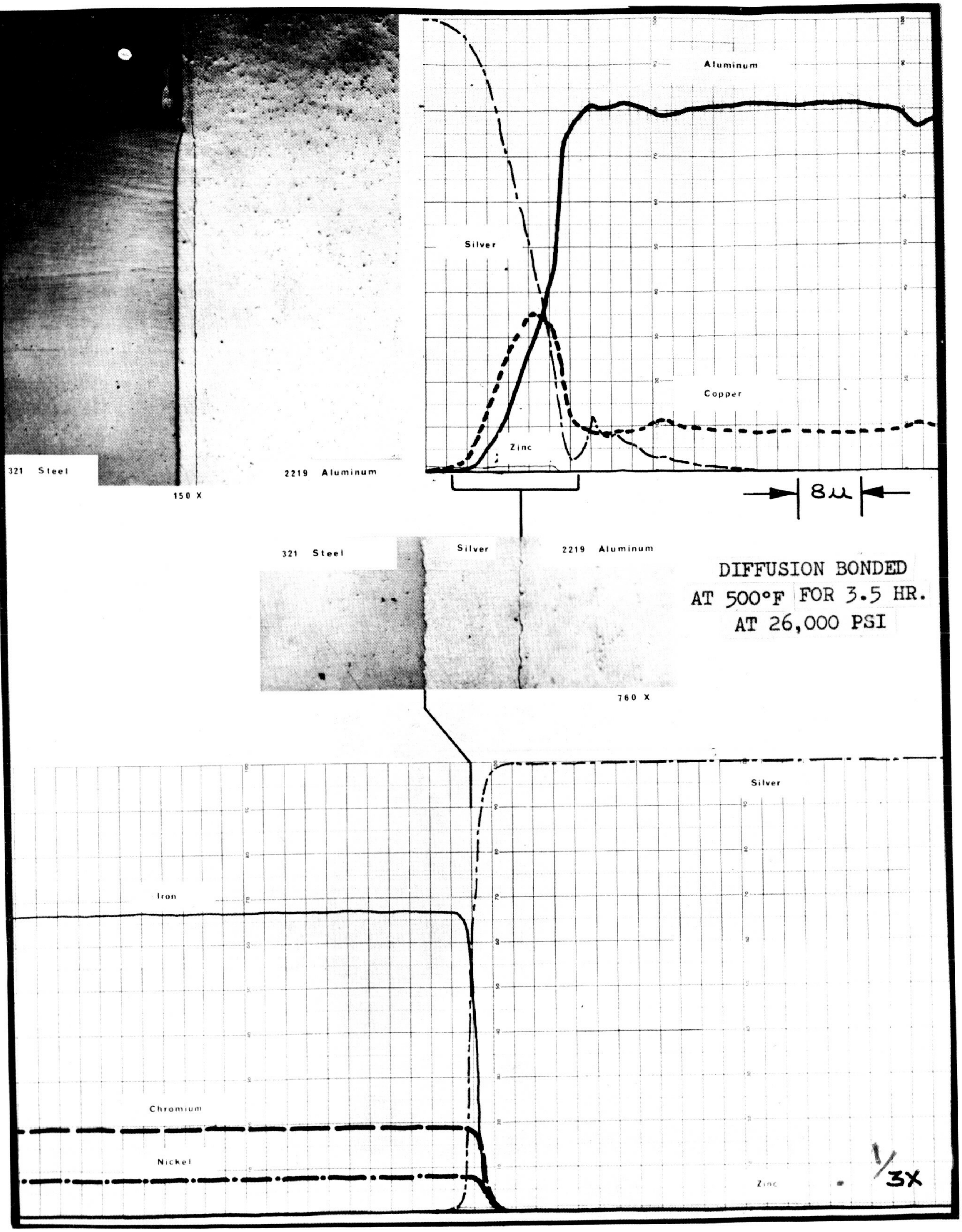


FIGURE 11 SUMMARY OF ELECTRON MICROPROBE ANALYSIS OF DIFFUSION BONDED JOINT

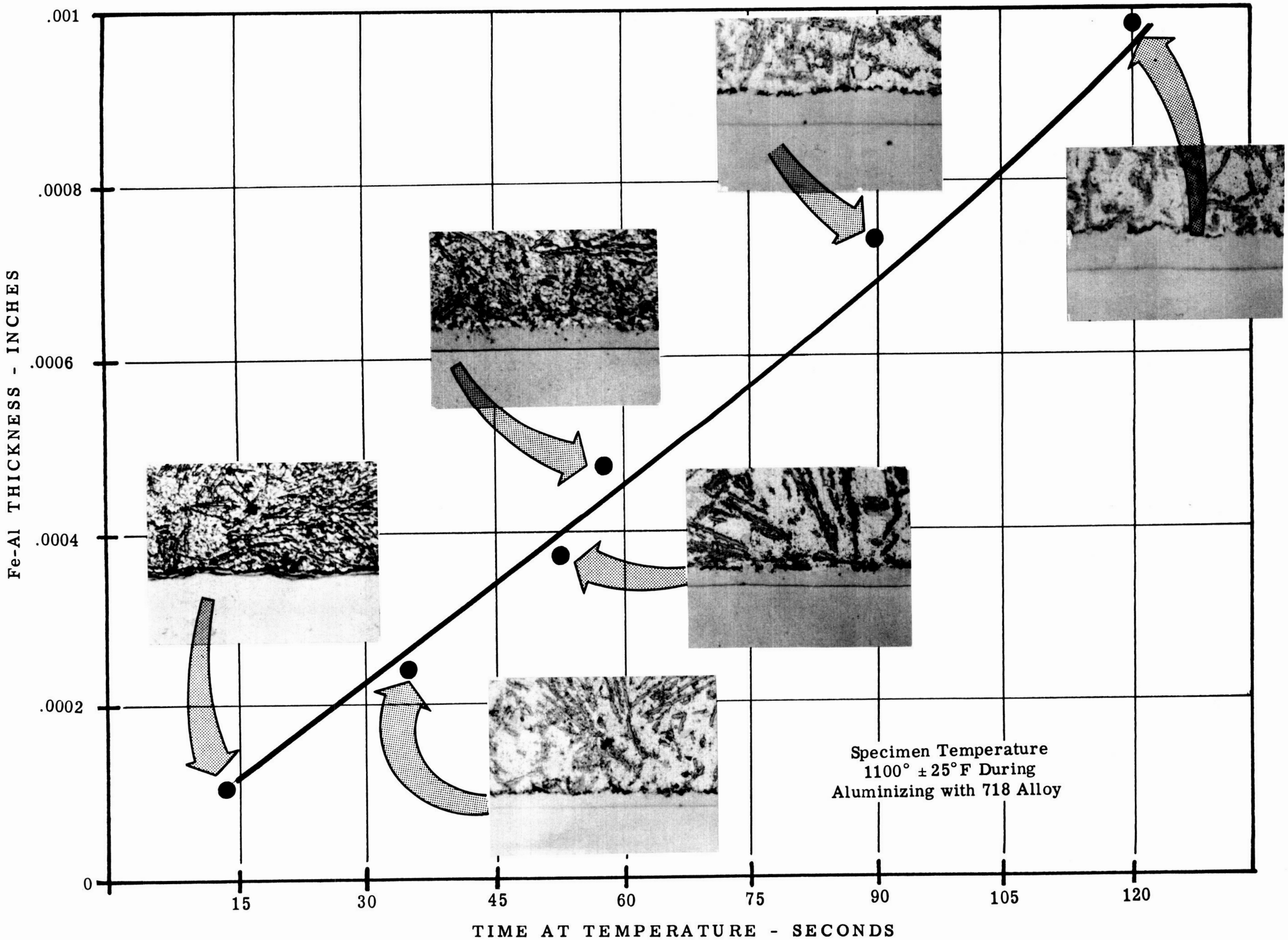
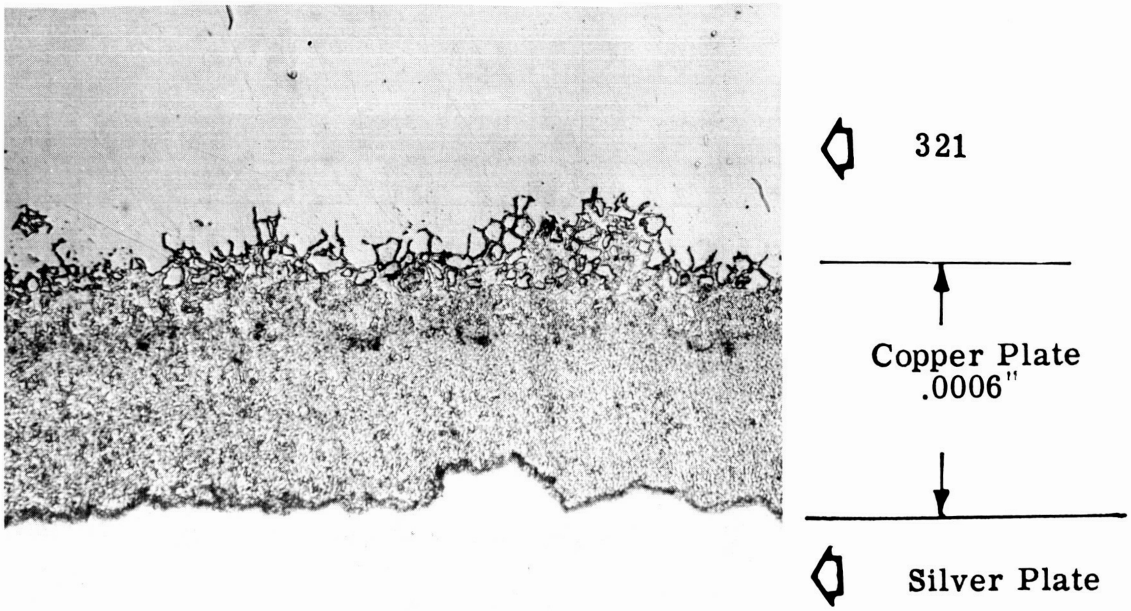
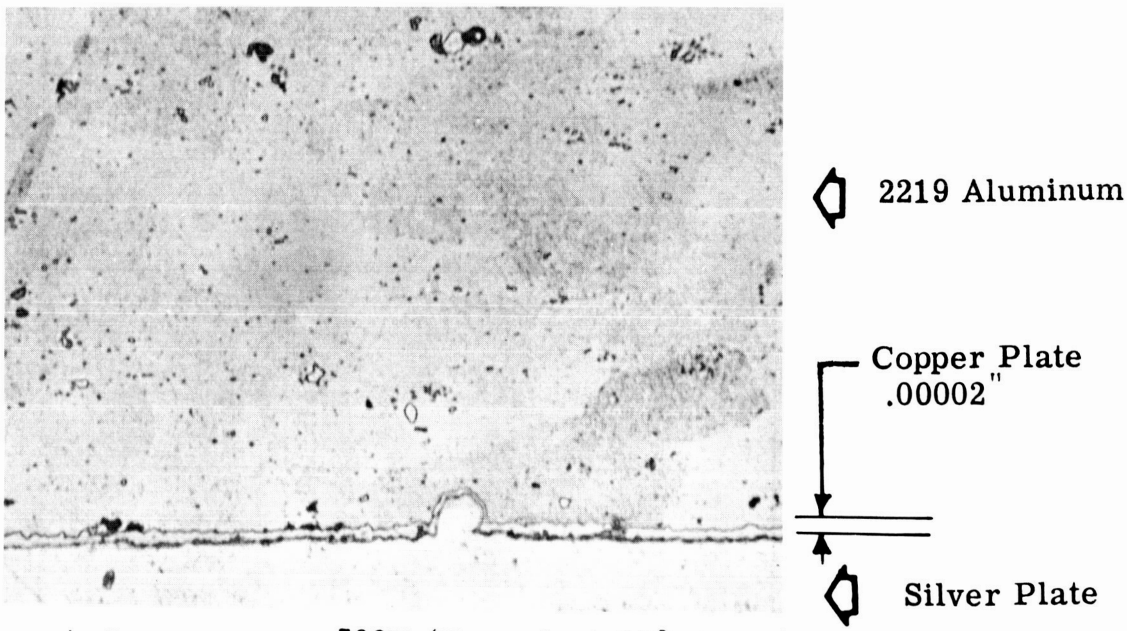


FIGURE 12: EFFECT OF ALUMINIZING TIME ON THICKNESS OF Fe-Al DIFFUSION ZONE



Dilute Nital Etch 500X (Viewed at 15° Angle)

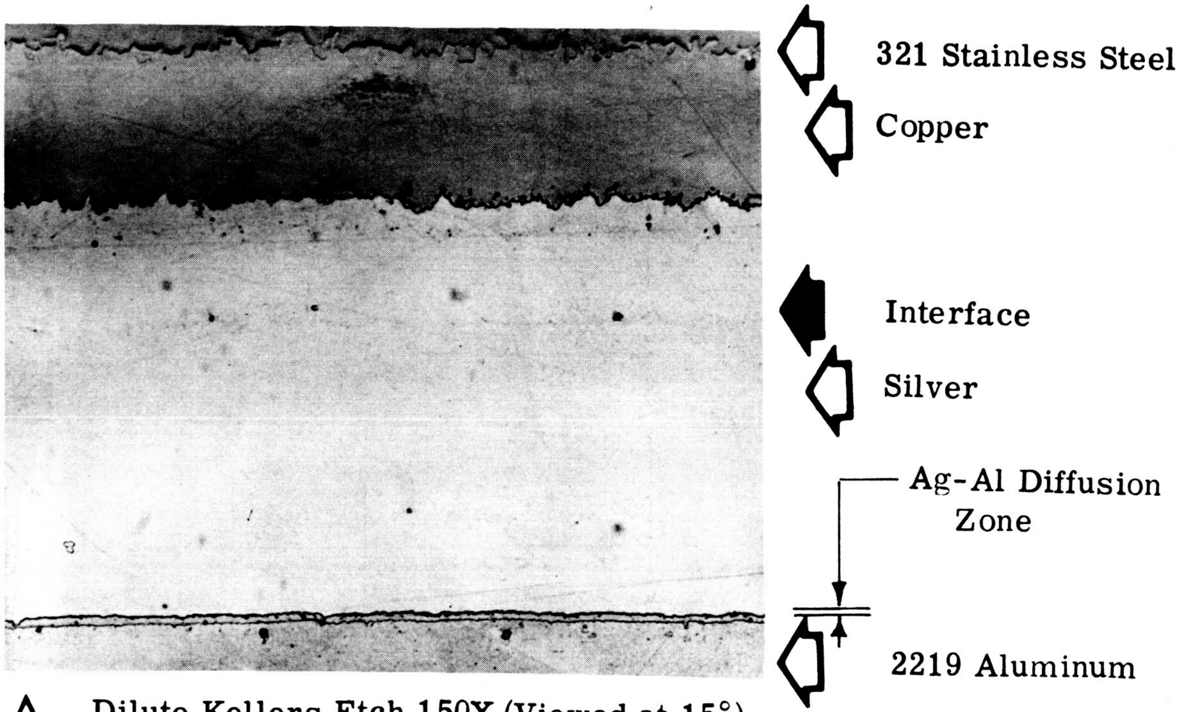
A 321 Stainless Steel Interface



1/2 % HF Etch 500X (Viewed at 15° Angle)

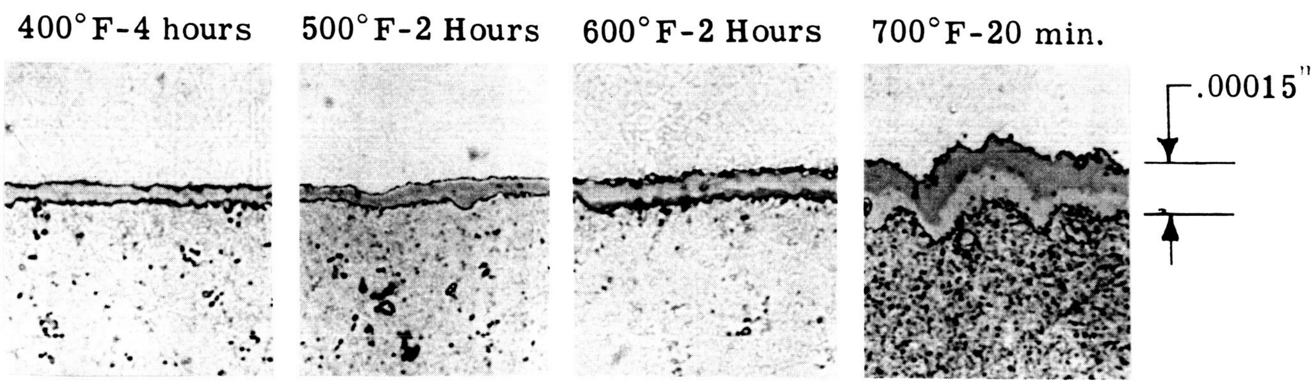
B 2219 Aluminum Alloy Interface

FIGURE 13: PHOTOMICROGRAPHS OF STAINLESS STEEL AND ALUMINUM INTERFACES AFTER PLATING AND PRIOR TO BONDING



A Dilute Kellers Etch 150X (Viewed at 15°)

Diffusion Bonded Joint (600°F - 2 hours)



B Dilute Kellers Etch 500X (Viewed at 15°)

Silver - Aluminum Interface After Various Bonding Cycles

FIGURE 14: PHOTOMICROGRAPHS SHOWING THE EFFECT OF BONDING TIME AND TEMPERATURE ON THE GROWTH OF THE SILVER-ALUMINUM DIFFUSION ZONE

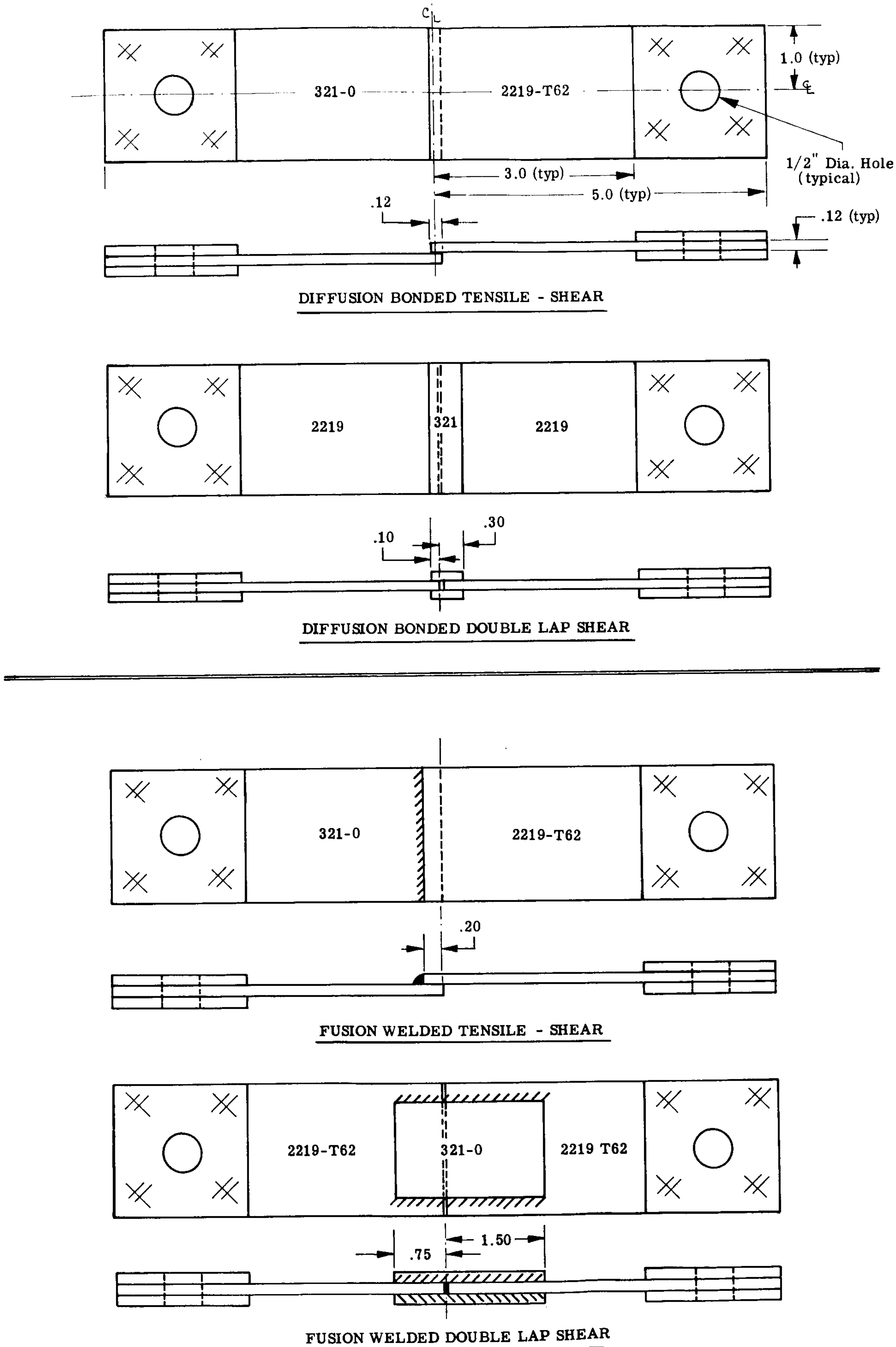
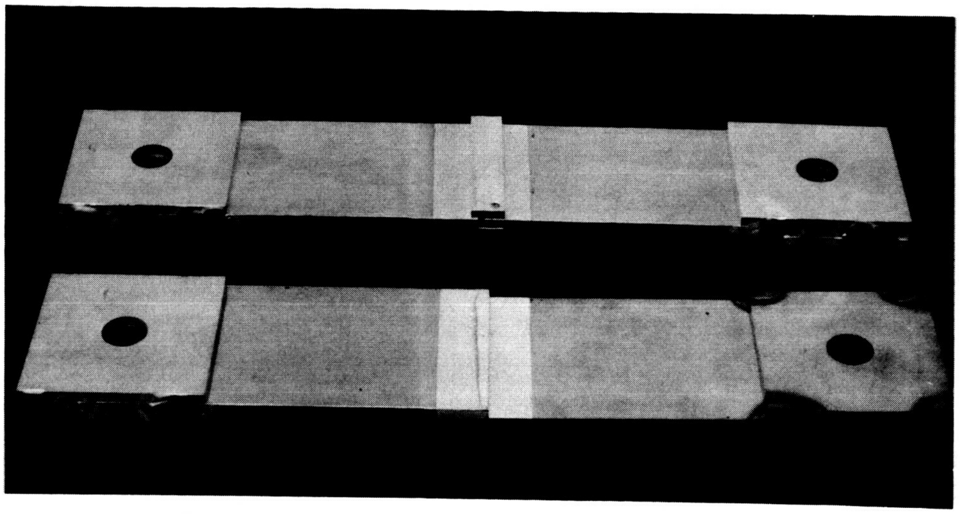
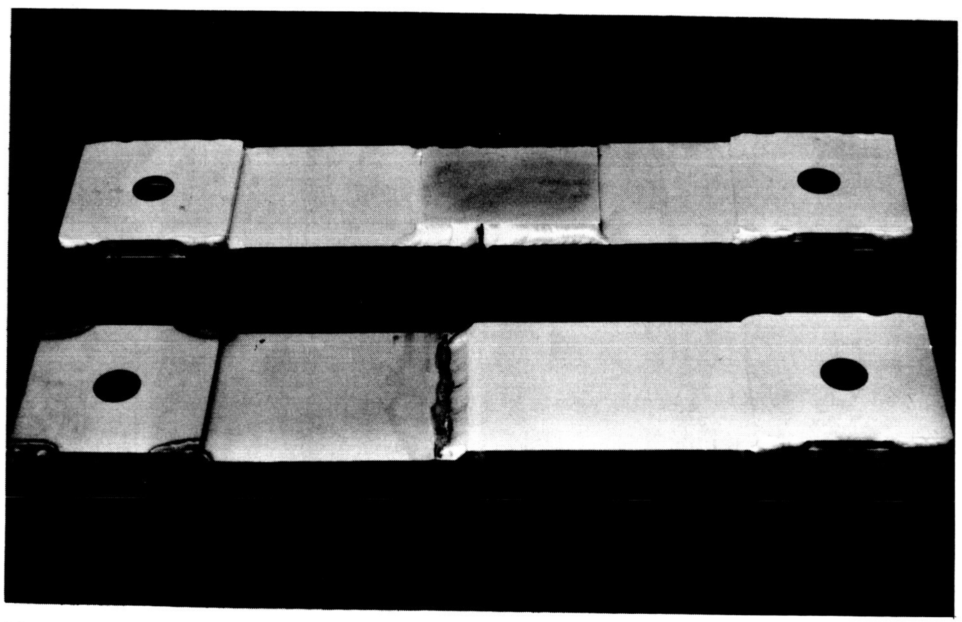


FIGURE 15 SPECIMEN CONFIGURATIONS

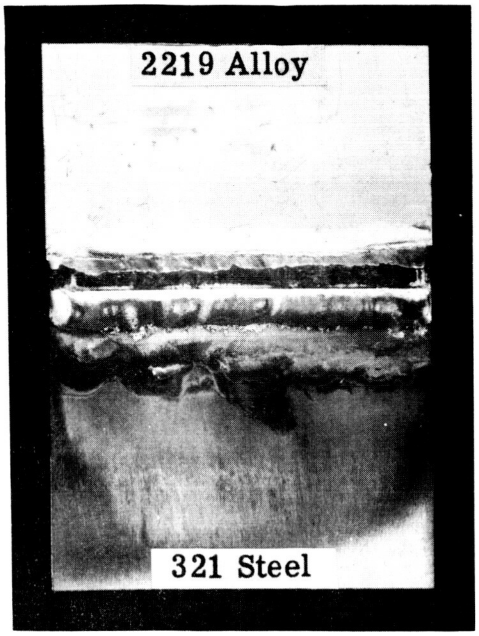


A Joined by Diffusion Bonding

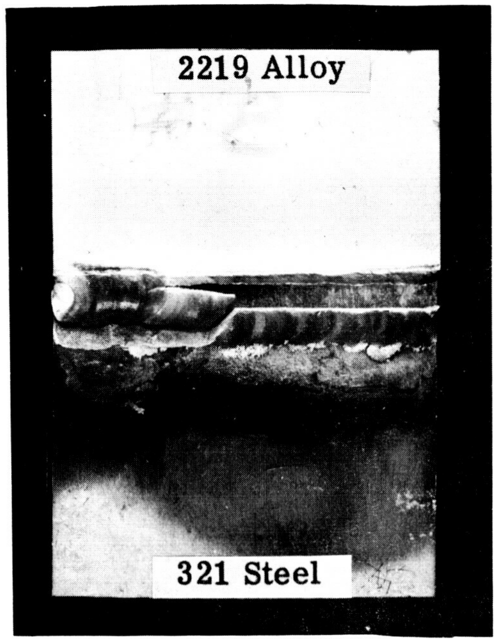


B Joined by GTA Welding

FIGURE 16 SHEAR SPECIMENS - 321 STAINLESS STEEL JOINED TO 2219 ALUMINUM ALLOY

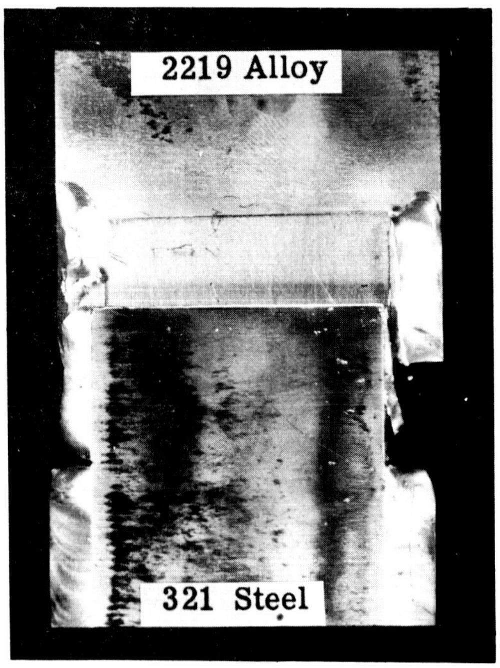


70°F Test

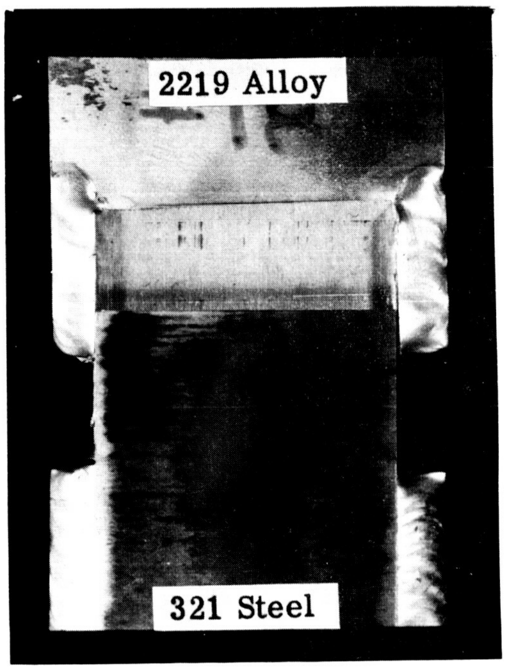


-423°F Test

A SINGLE LAP SHEAR



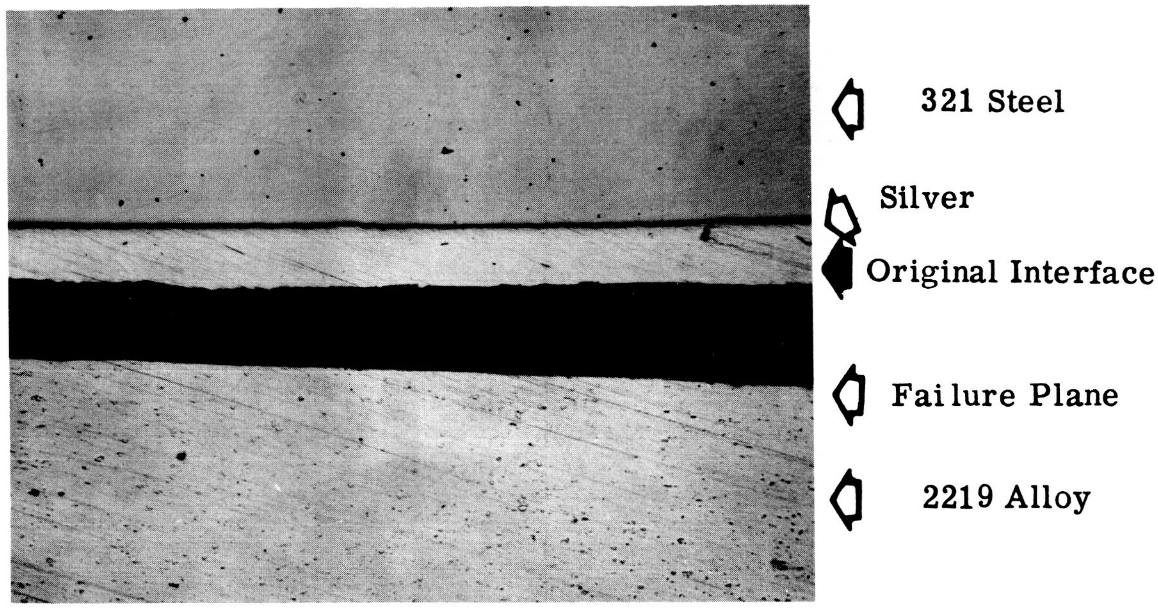
70°F Test



-423°F Test

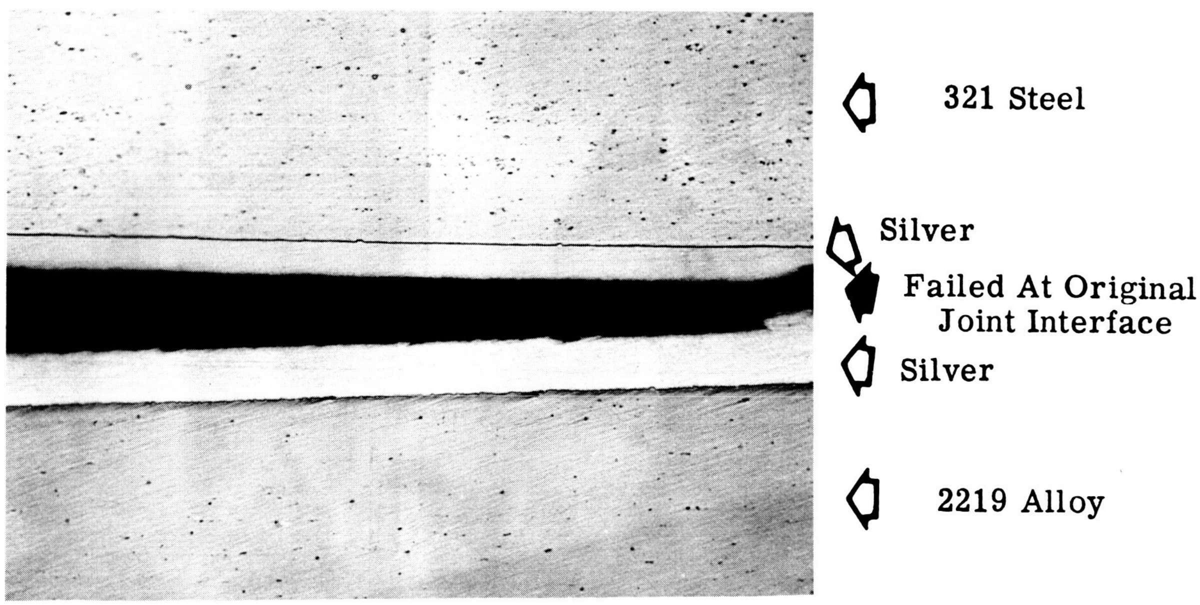
B DOUBLE LAP SHEAR

FIGURE 17 FUSION WELDED SHEAR SPECIMENS AFTER FAILURE
(2219 Aluminum To 321 Stainless Steel)



Unetched 100X

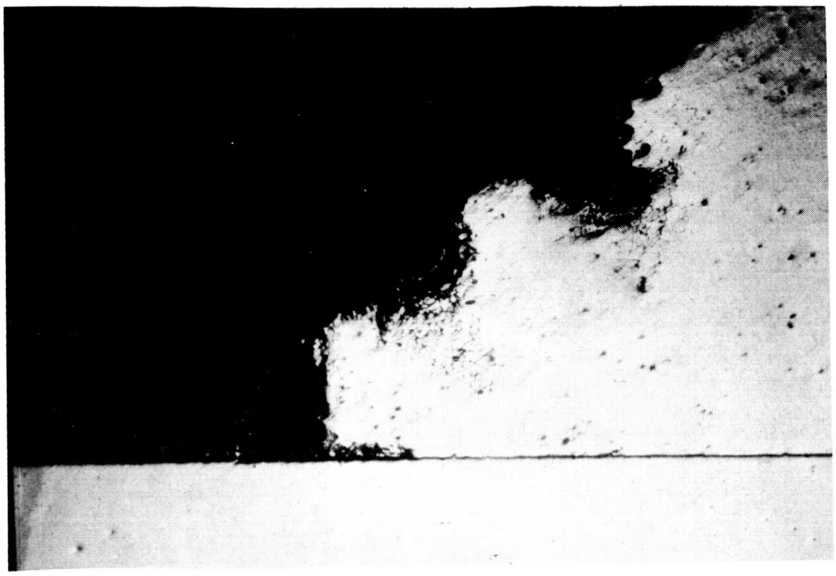
A SINGLE LAP SHEAR -423°F TEST



Unetched 100X

B DOUBLE LAP SHEAR -423°F TEST

FIGURE 18 DIFFUSION BONDED SHEAR SPECIMENS AFTER TEST
(2219 Aluminum To 321 Stainless Steel)



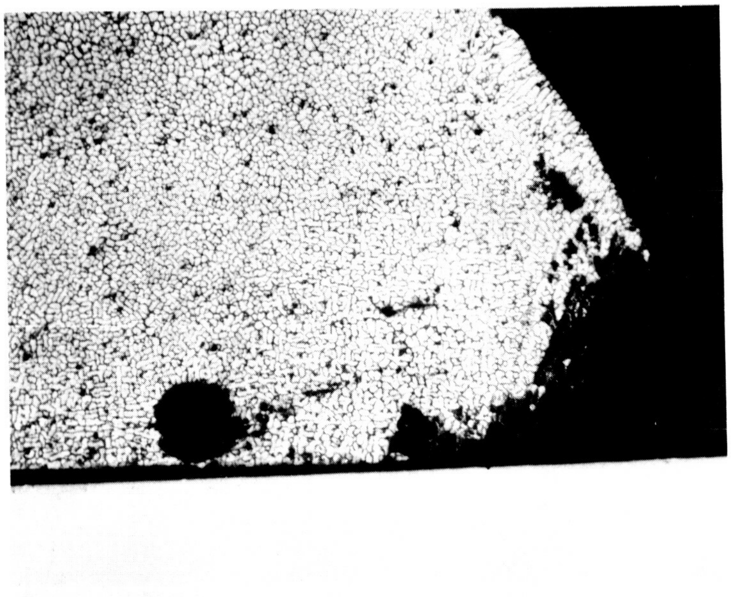
4043 Filler Metal

321 Steel

A Unetched 50X

After 72 Hours in 5% NaCl Spray

4043 Filler Alloy

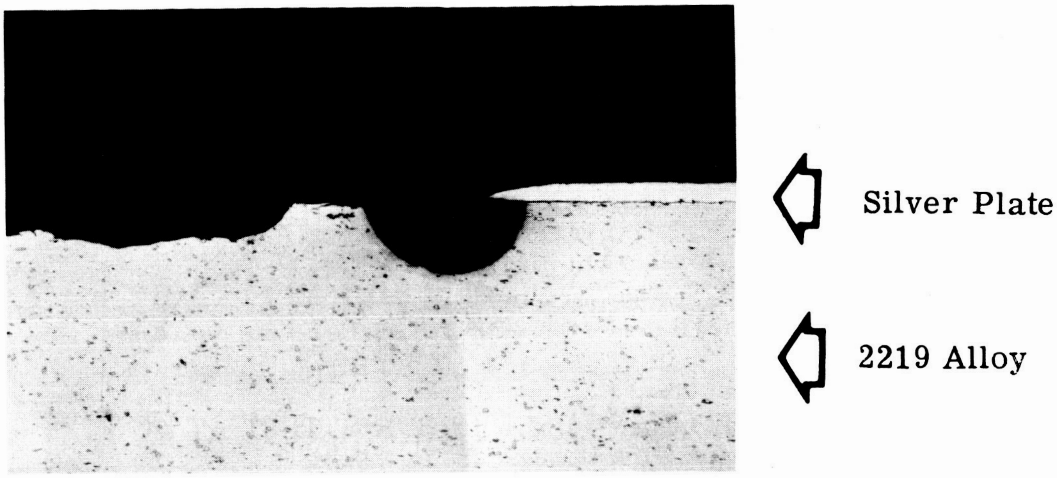


321

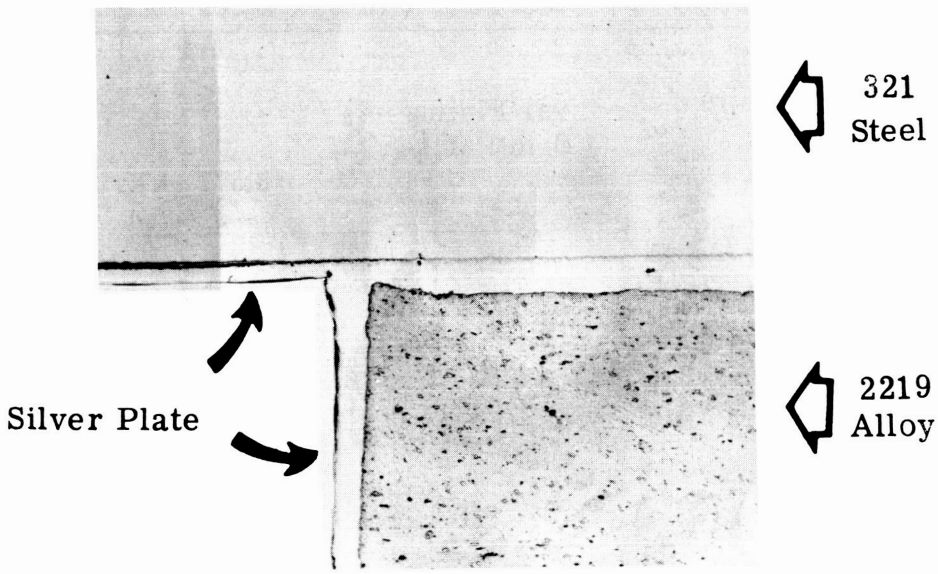
B Dilute Keller's Etch 50X

After 144 Hours in NaCl Spray

FIGURE 19 CORROSION SPECIMEN - 321 STAINLESS STEEL GTA WELDED TO 2219 ALUMINUM ALLOY

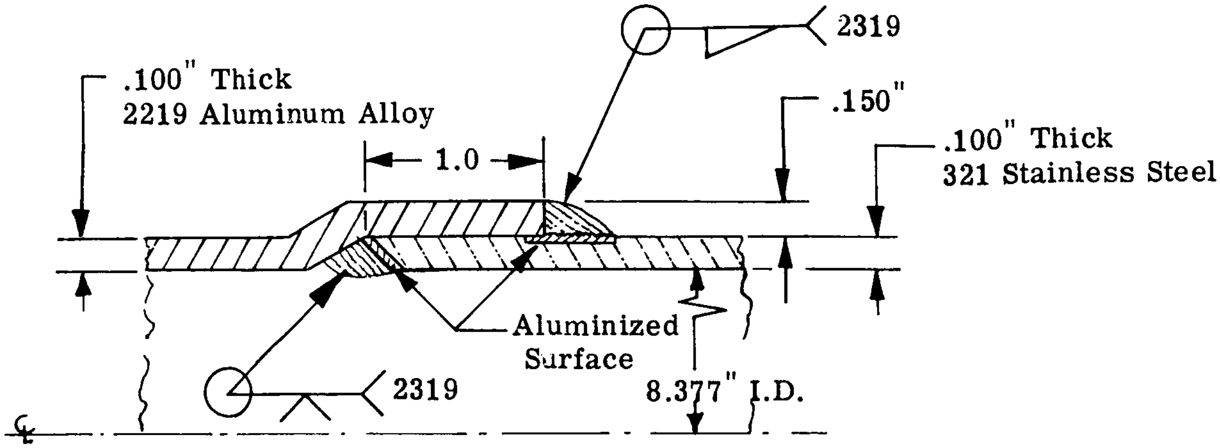


A Dilute Keller's Etch 75X

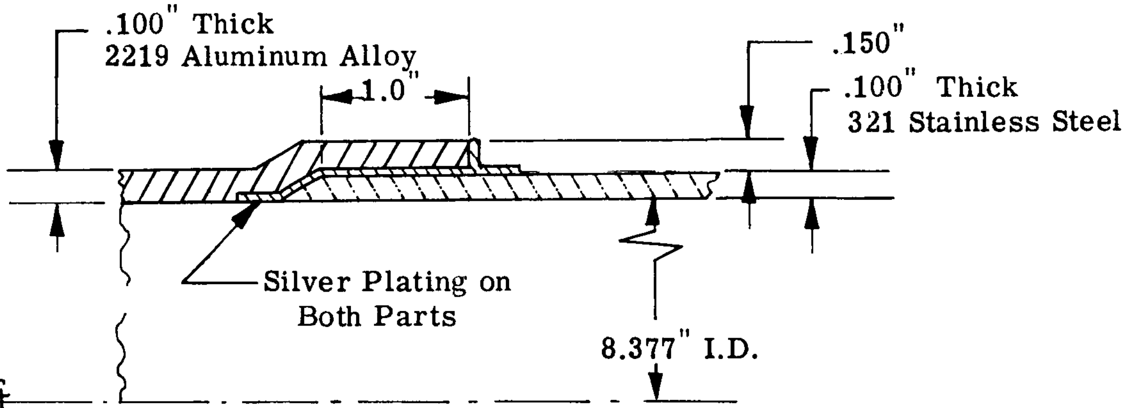


B Dilute Keller's Etch 75X

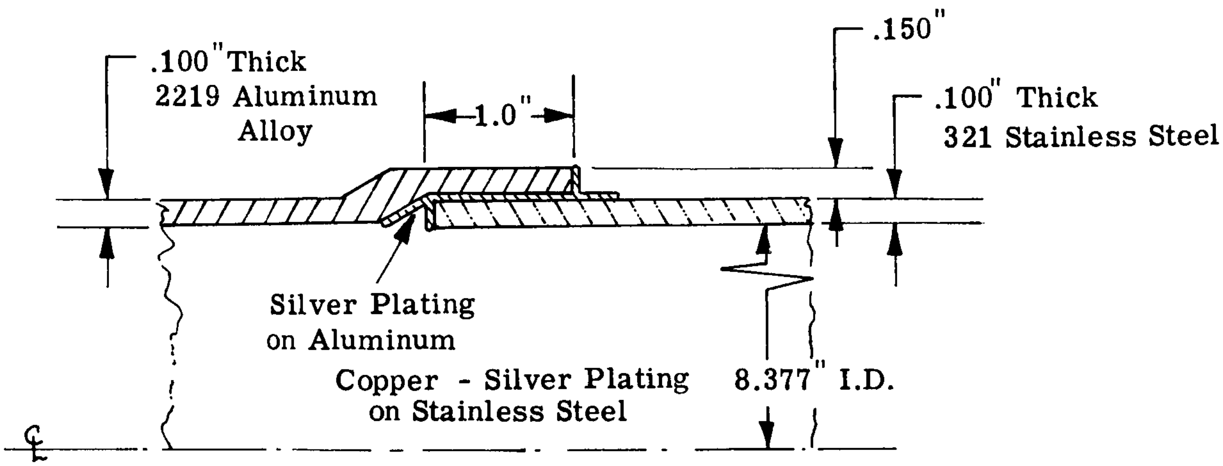
FIGURE 20 CORROSION SPECIMEN-SILVER PLATED 321 STEEL DIFFUSION BONDED TO SILVER PLATED 2219 ALUMINUM ALLOY AFTER 144 HOURS IN 5% NaCl SPRAY



A. CROSS SECTION OF WELDED JOINT USED IN BURST TEST AT 70°F.

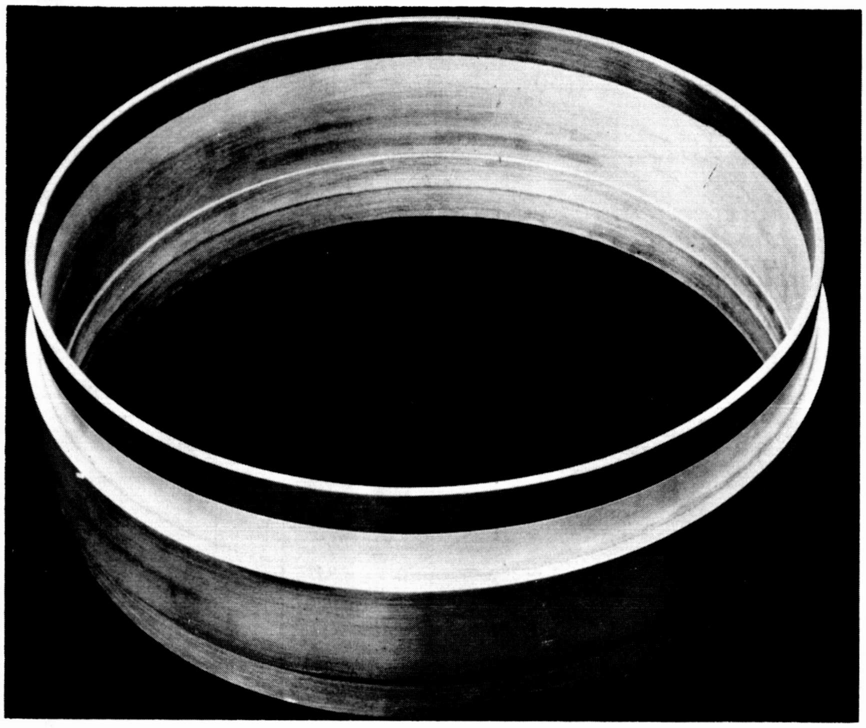


B. CROSS SECTION OF DIFFUSION BONDED JOINT USED IN BURST TEST AT 70°F.



C. CROSS SECTION OF DIFFUSION BONDED JOINT USED IN BURST TEST AT -320°F.

FIGURE 21: CROSS SECTION OF JOINTS USED IN EIGHT-INCH DIAMETER TANKS



A Joined by Diffusion Bonding

B Joined by GTA Welding

FIGURE 22 EIGHT INCH DIAMETER STAINLESS STEEL RING JOINED TO 2219 ALUMINUM ALLOY RING BY DIFFUSION BONDING AND WELDING

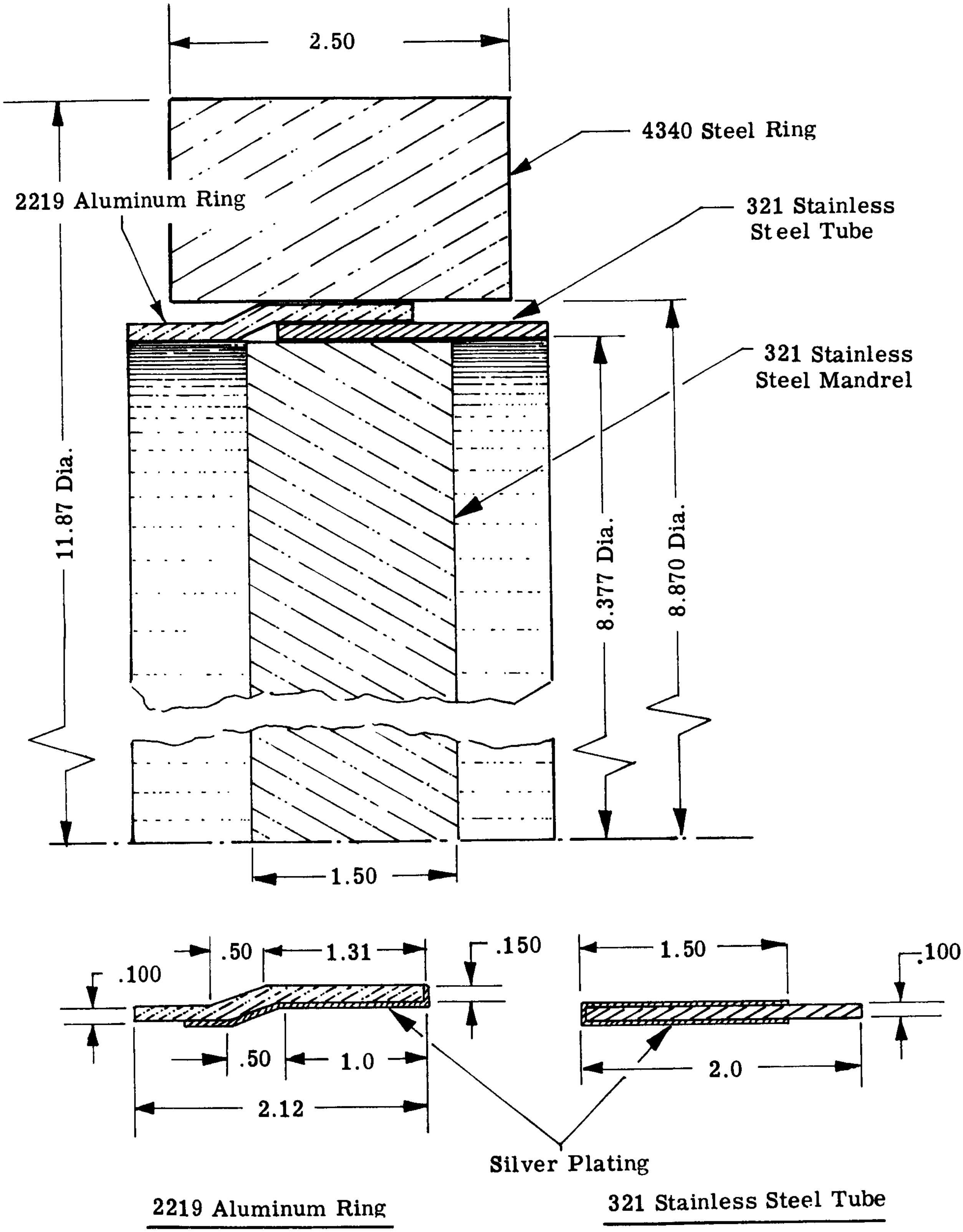
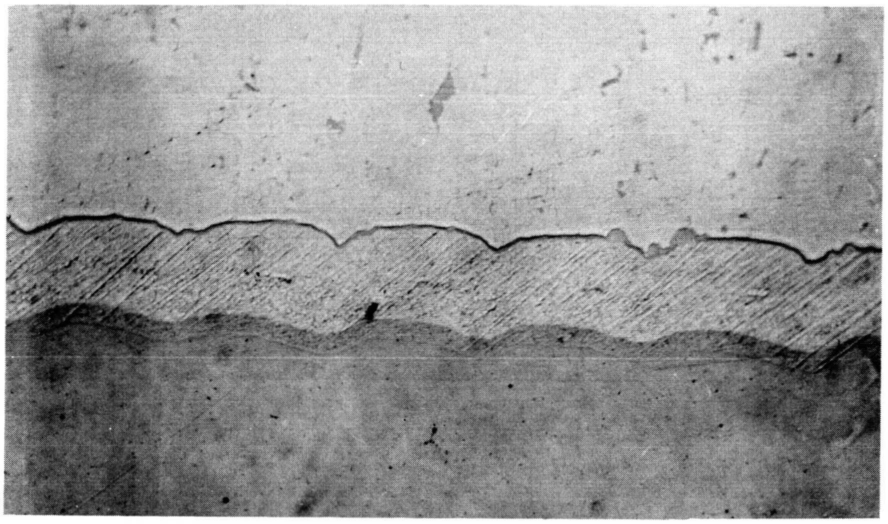
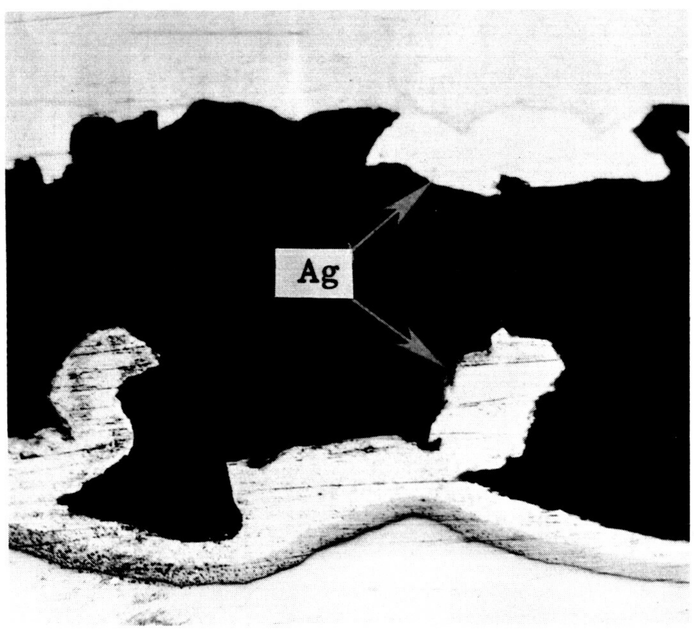


FIGURE 23: ARRANGEMENT FOR DIFFUSION BONDING EIGHT-INCH DIAMETER ASSEMBLIES



Unetched 250X

A. Diffusion Bonded Joint Before Peel Test



Unetched 500X

B. Diffusion Bonded Joint After Peel Test

1 Surface Waviness is a Result of Machining

FIGURE 24: APPEARANCE OF A DIFFUSION BONDED JOINT TAKEN FROM A EIGHT-INCH DIAMETER RING
(500°F, 4 Hours plus 650°F-1 Hour)

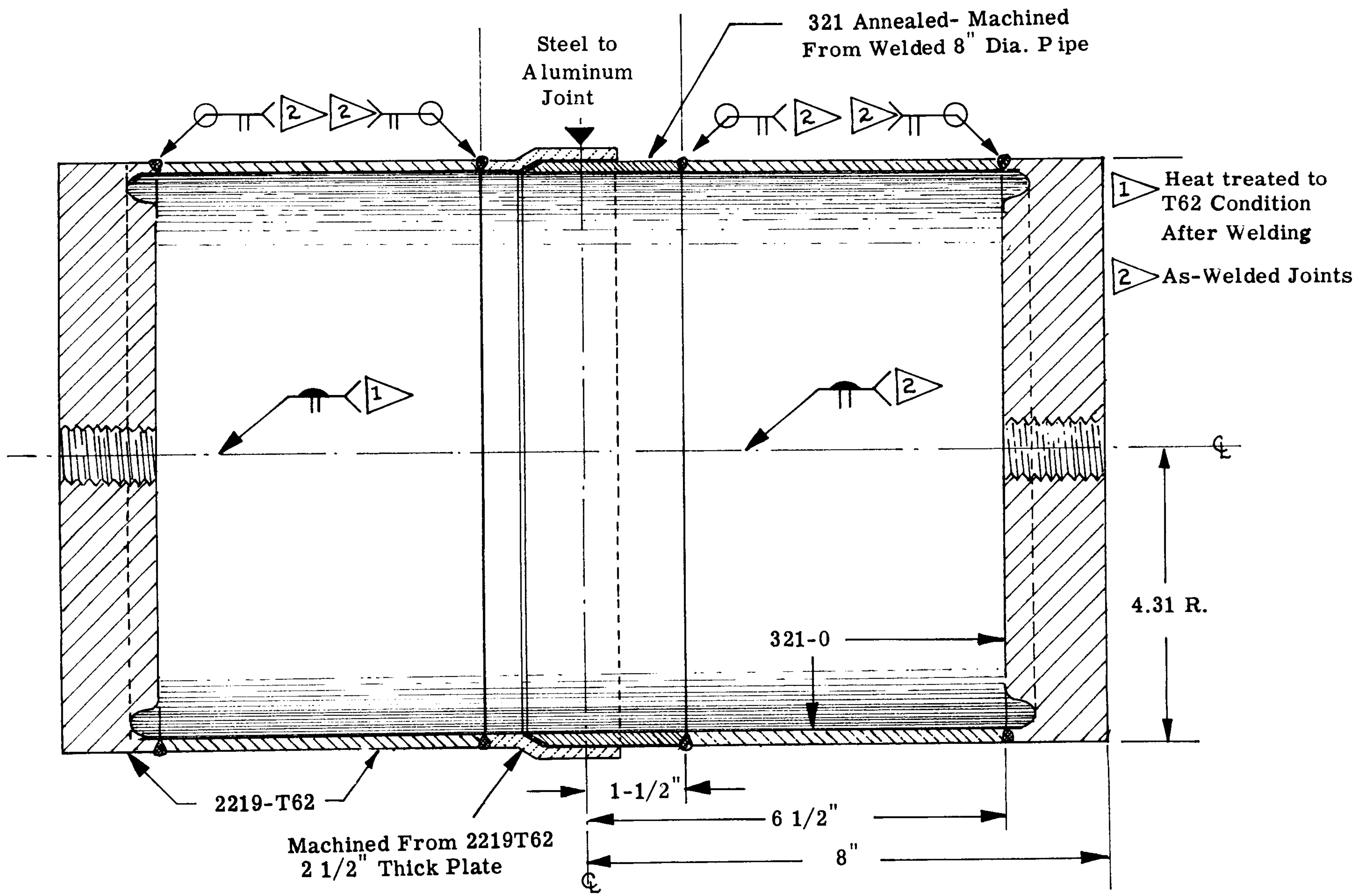
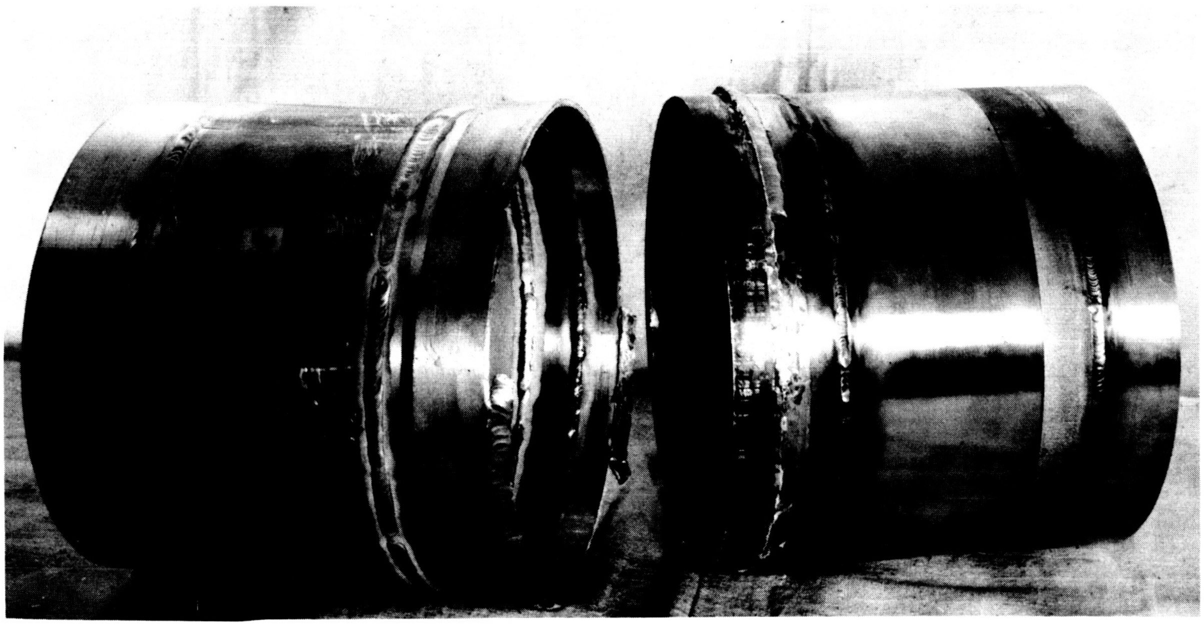
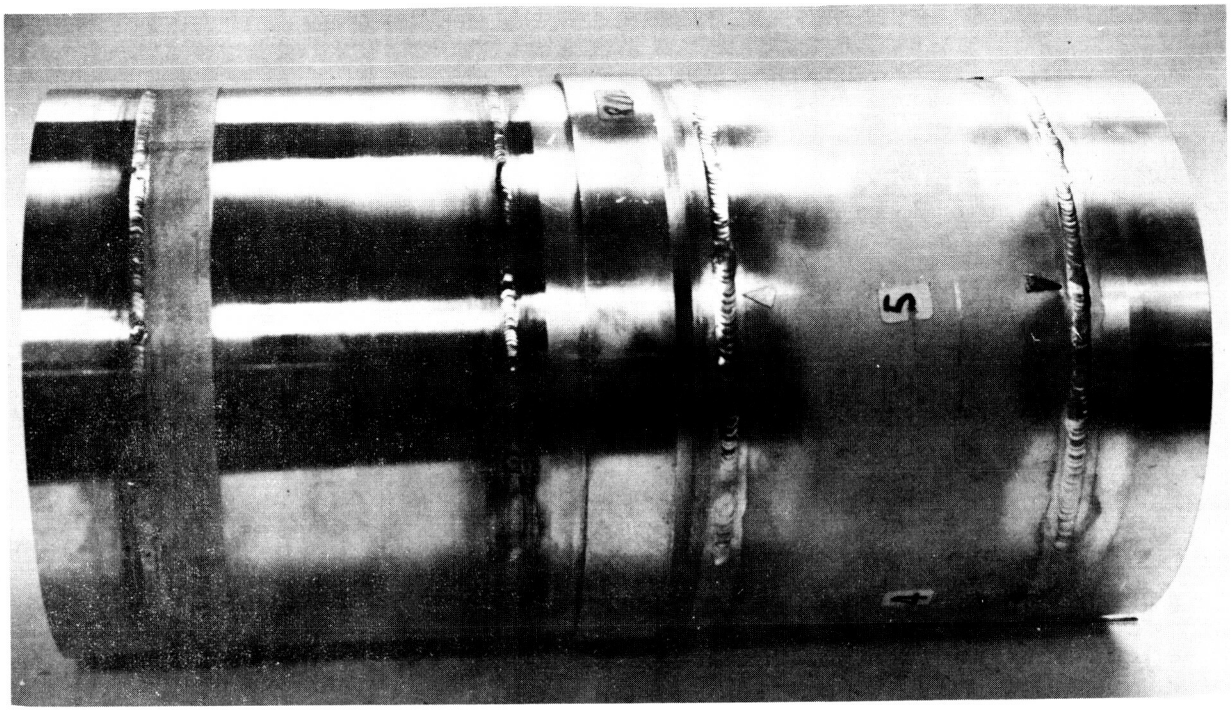


FIGURE 25 EIGHT INCH DIAMETER TEST TANK



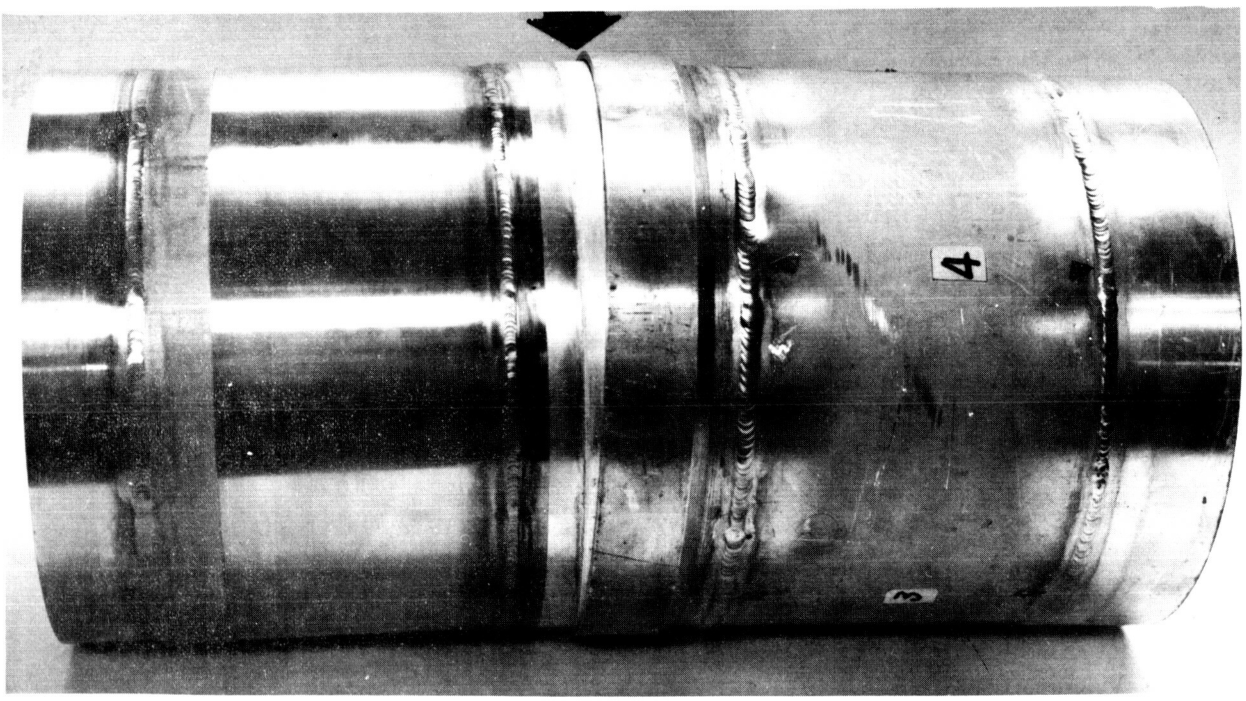
321 Stainless Steel Joined To 2219 Aluminum Alloy By Welding
(Room Temperature Test - Failed at 650 PSIG)

FIGURE 26. PHOTOGRAPH OF EIGHT-INCH DIAMETER WELDED TEST ASSEMBLY AFTER BURST TEST



A PRIOR TO BURST TEST

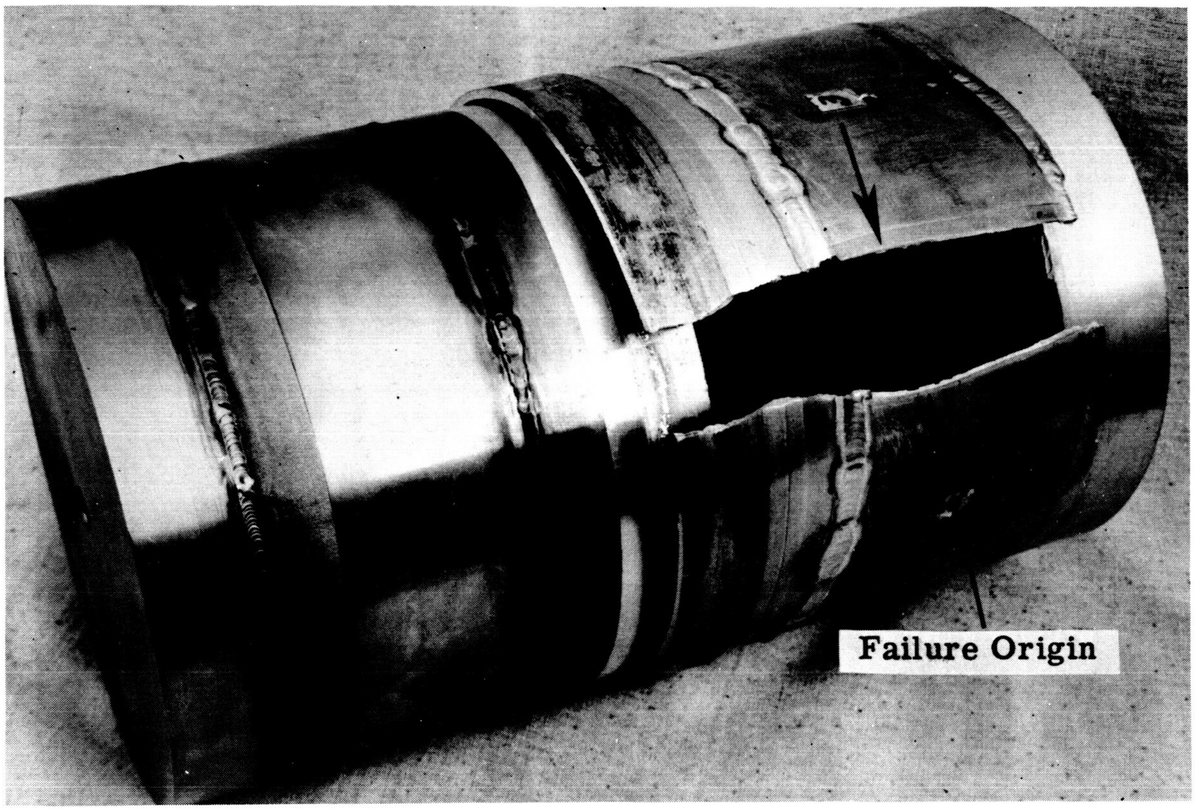
Shear Failure



B AFTER BURST TEST

(Room Temperature Test - Failed at 550 PSIG)

FIGURE 27 EIGHT INCH DIAMETER TANK 321 STAINLESS STEEL DIFFUSION BONDED TO 2219 ALUMINUM ALLOY.



321 Stainless Steel Joined To 2219 Aluminum Alloy by Diffusion Bonding (-320°F Test- Failed at 1440 PSIG)

FIGURE 28. PHOTOGRAPH OF EIGHT-INCH DIAMETER DIFFUSION BONDED ASSEMBLY AFTER BURST TEST AT -320°F

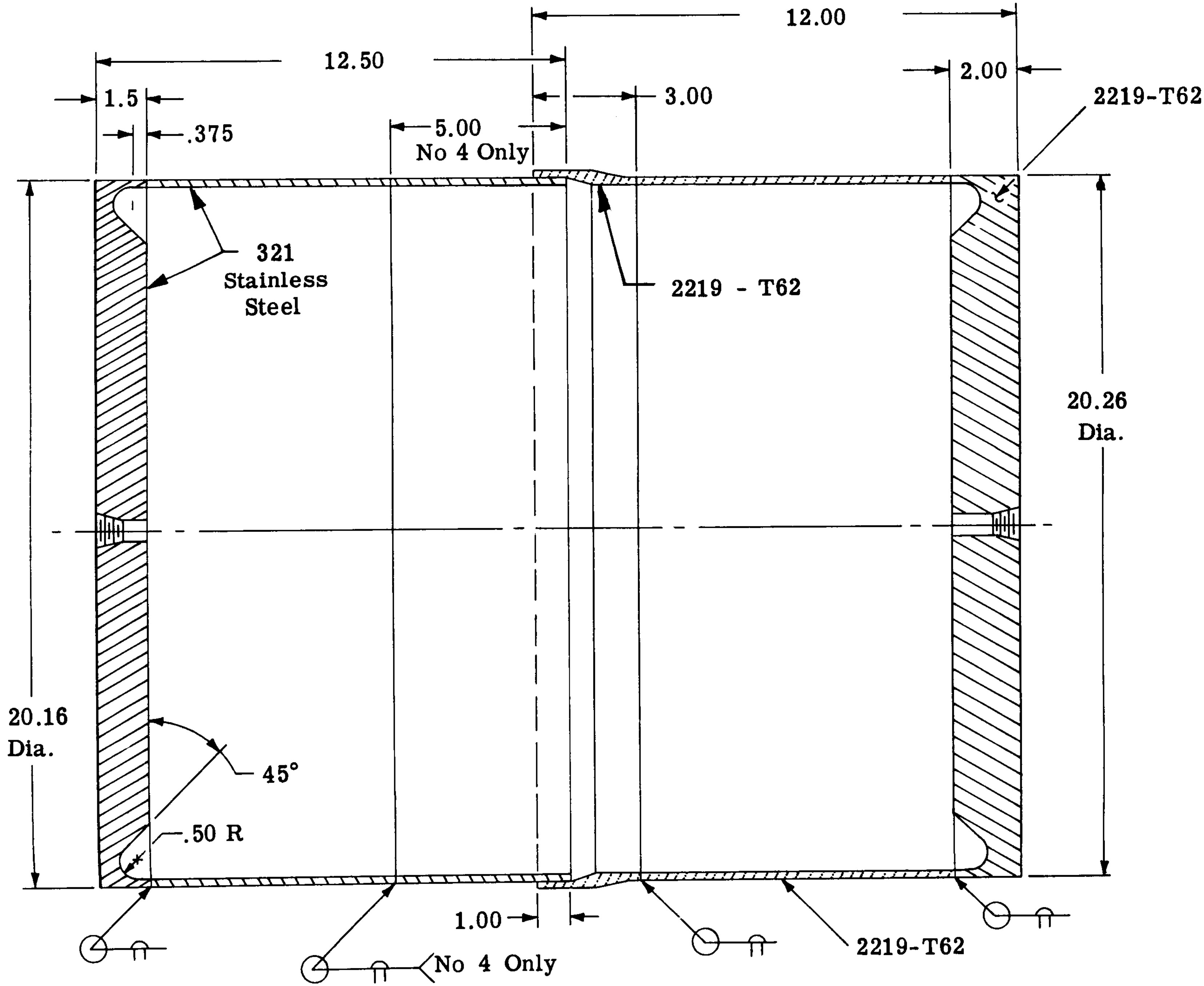


FIG. 29 CROSS SECTION OF TEST TANK

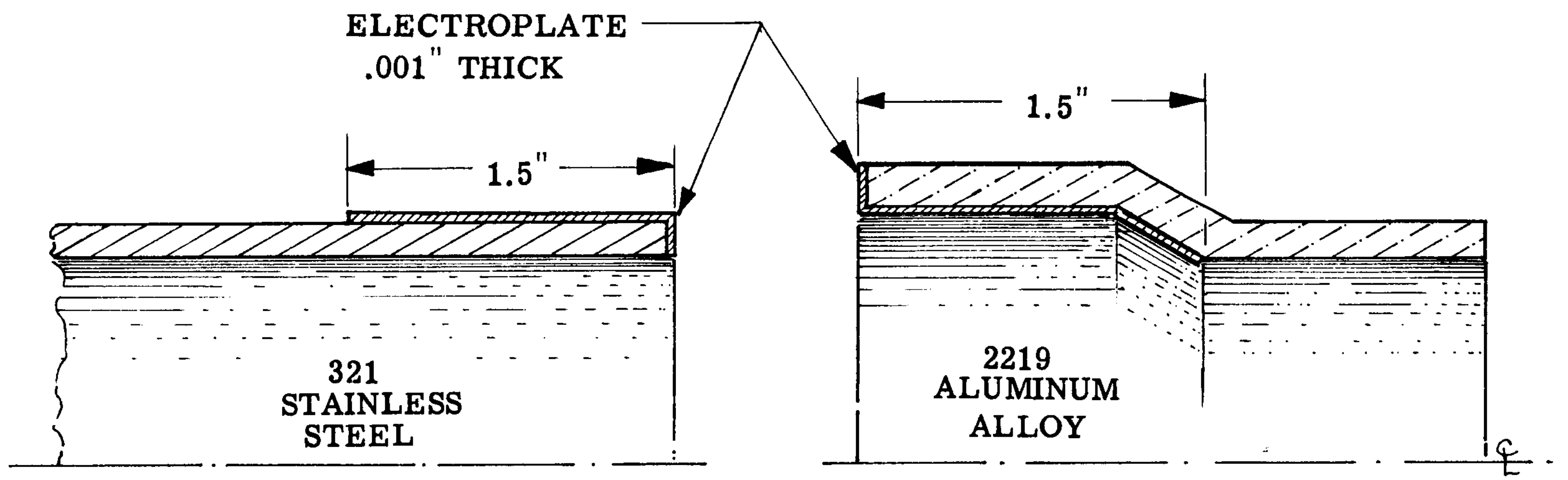


FIGURE 31 LOCATION OF ELECTROPLATE ON STAINLESS STEEL TUBE AND ALUMINUM RING

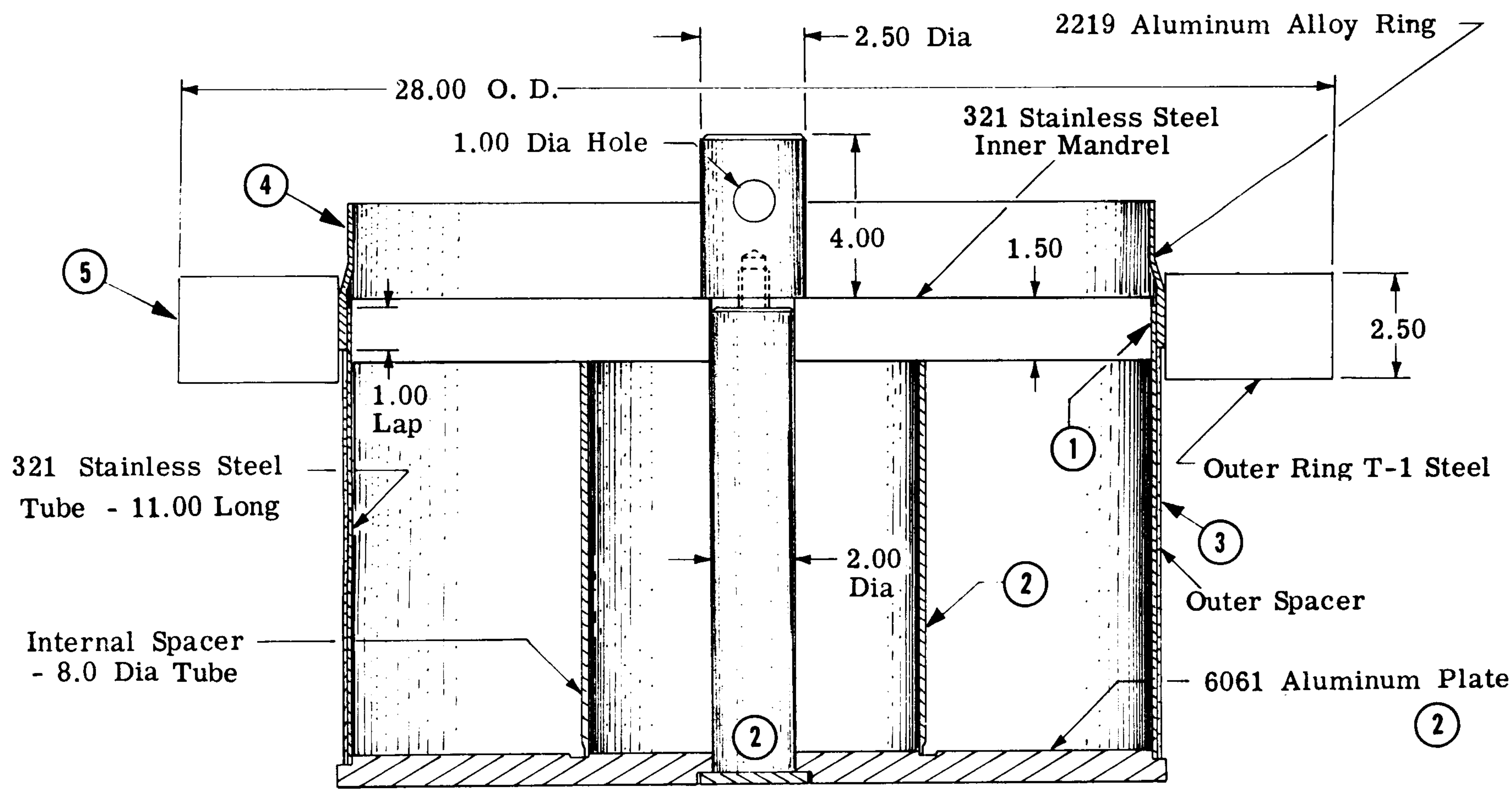


FIGURE 30 ARRANGEMENT OF PARTS DURING DIFFUSION BONDING

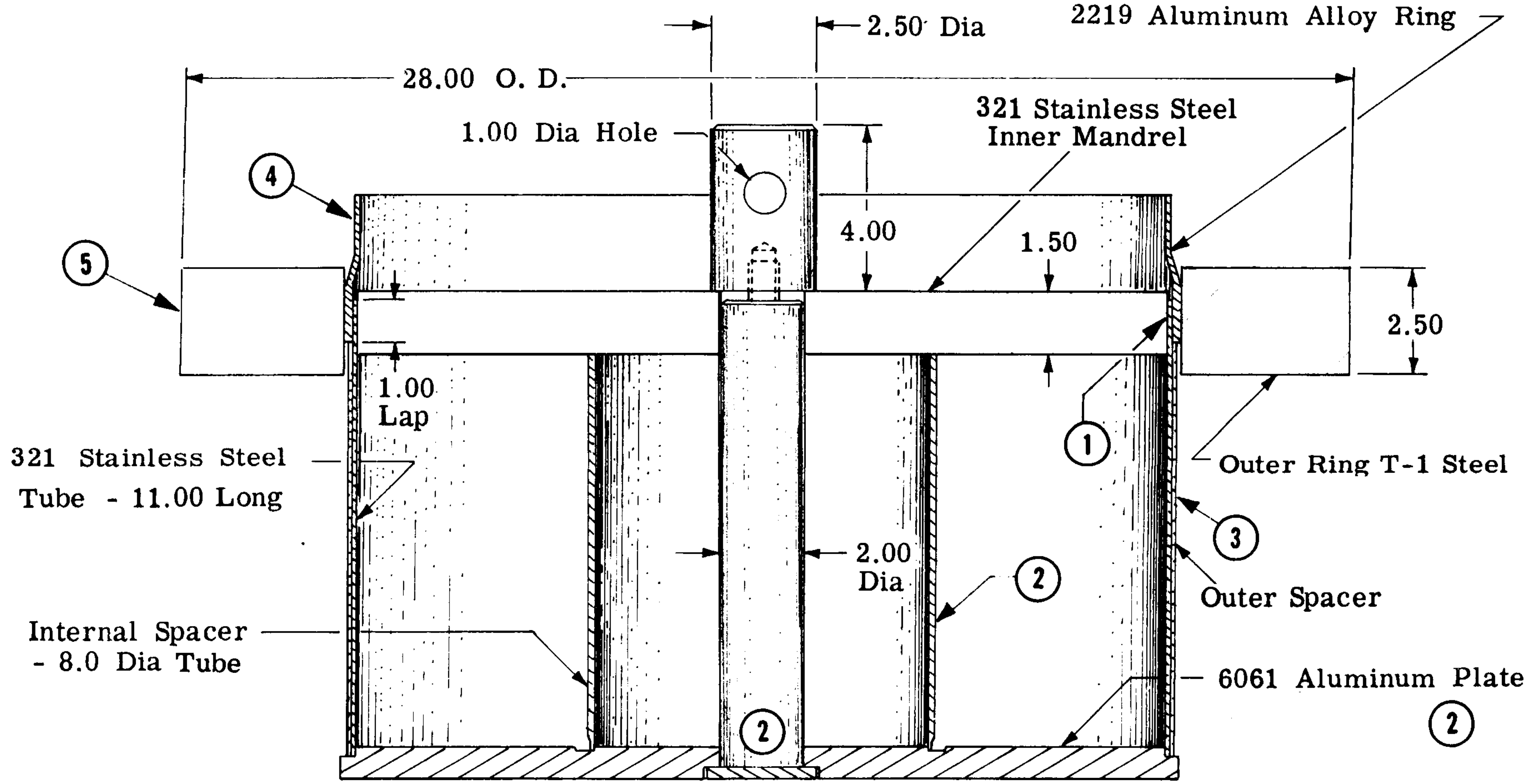


FIGURE 30 ARRANGEMENT OF PARTS DURING DIFFUSION BONDING

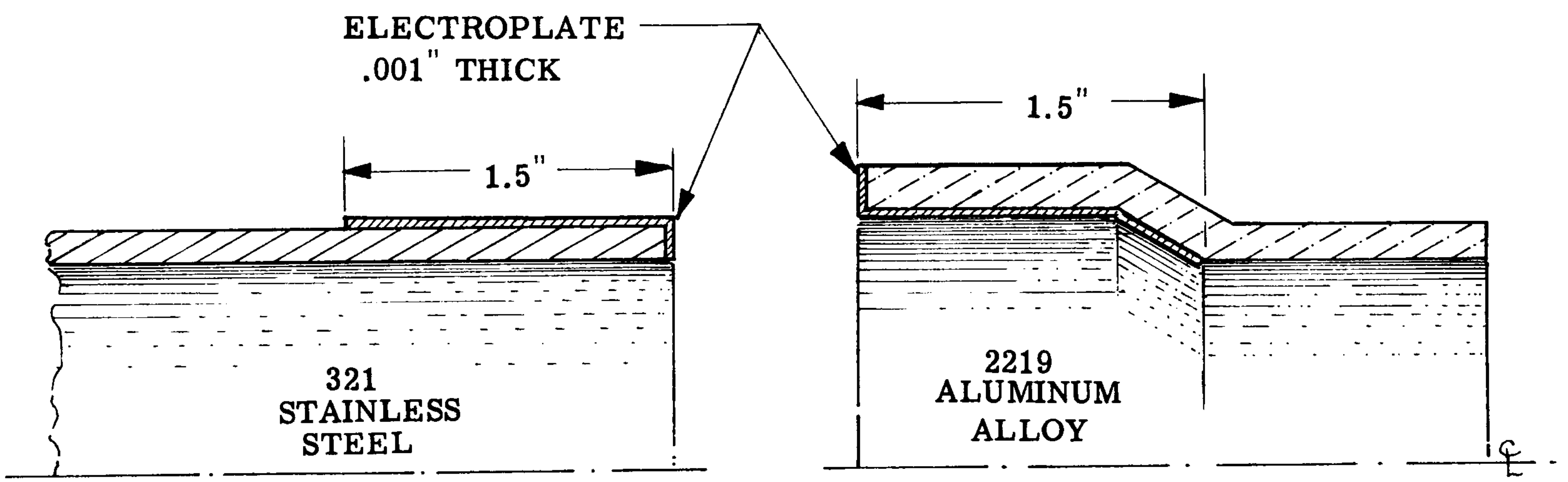


FIGURE 31 LOCATION OF ELECTROPLATE ON STAINLESS STEEL TUBE AND ALUMINUM RING

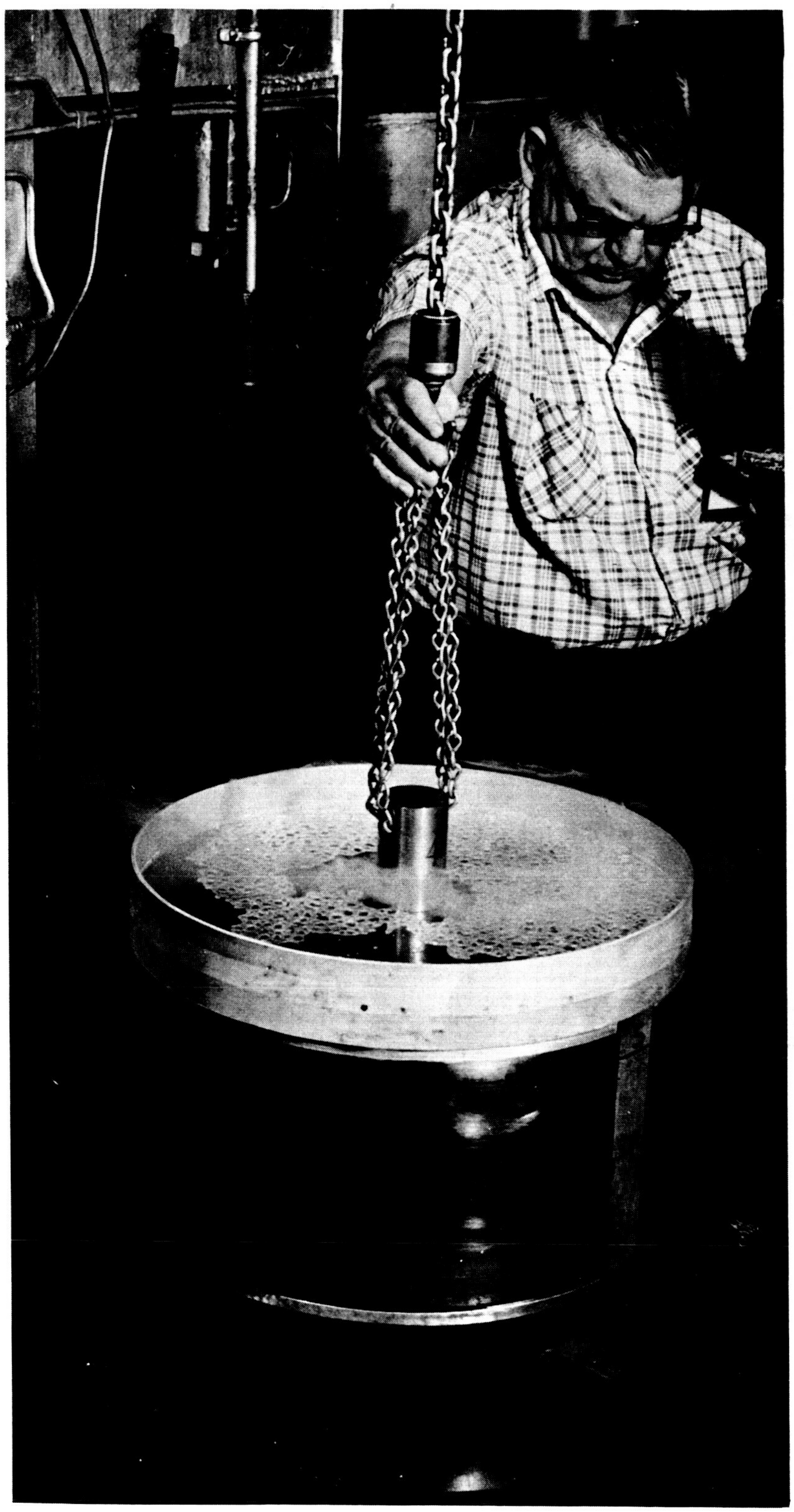


FIGURE 32

INSTALLATION OF DIFFUSION BOND ASSEMBLY NO. 1 INTO PREHEATED OUTER STEEL RING

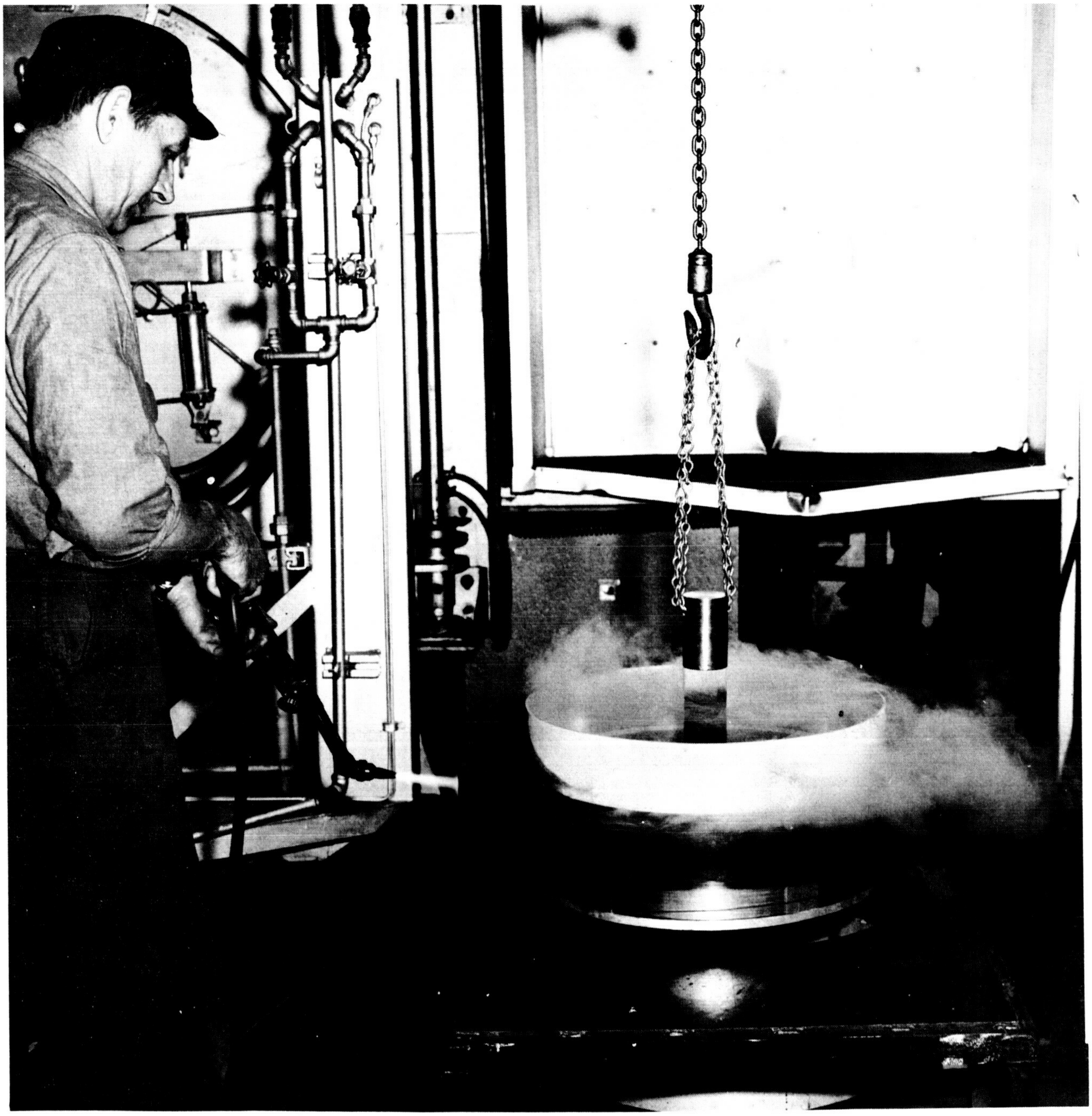


FIGURE 33

REMOVAL OF STEEL OUTER RING AFTER DIFFUSION BONDING

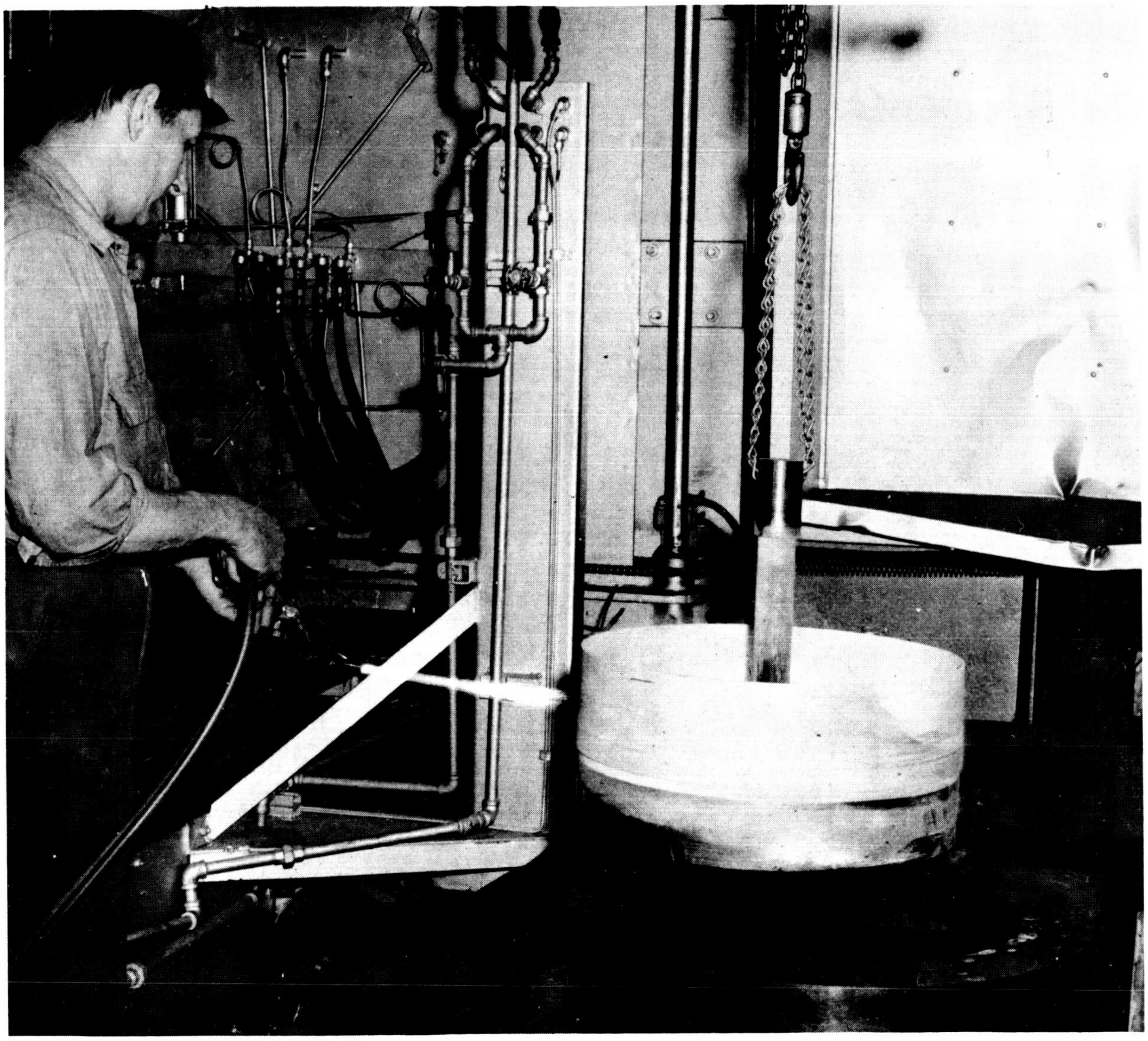
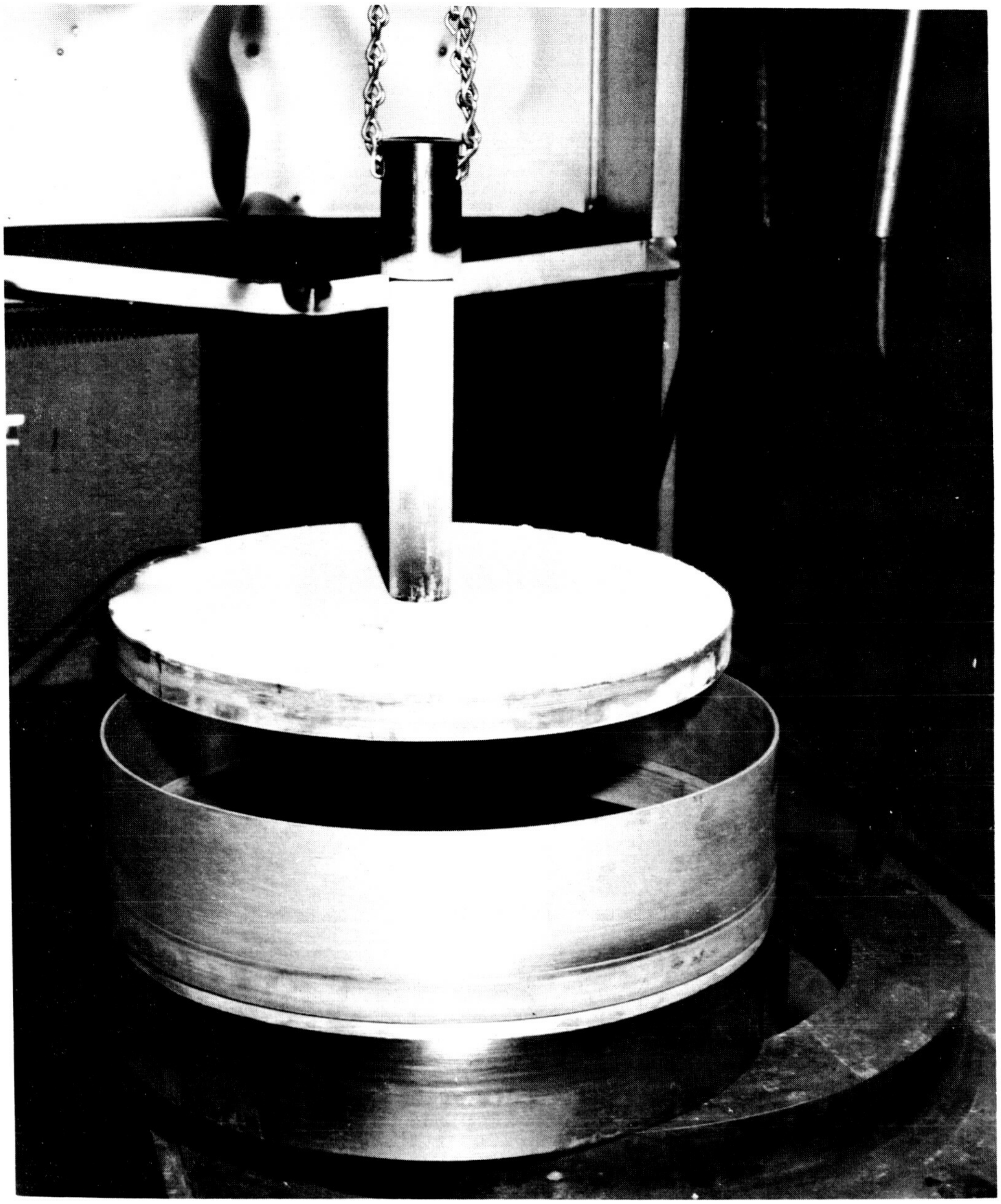


FIGURE 34

REMOVAL OF DIFFUSION BONDED ASSEMBLY NO. 4 FROM MANDREL



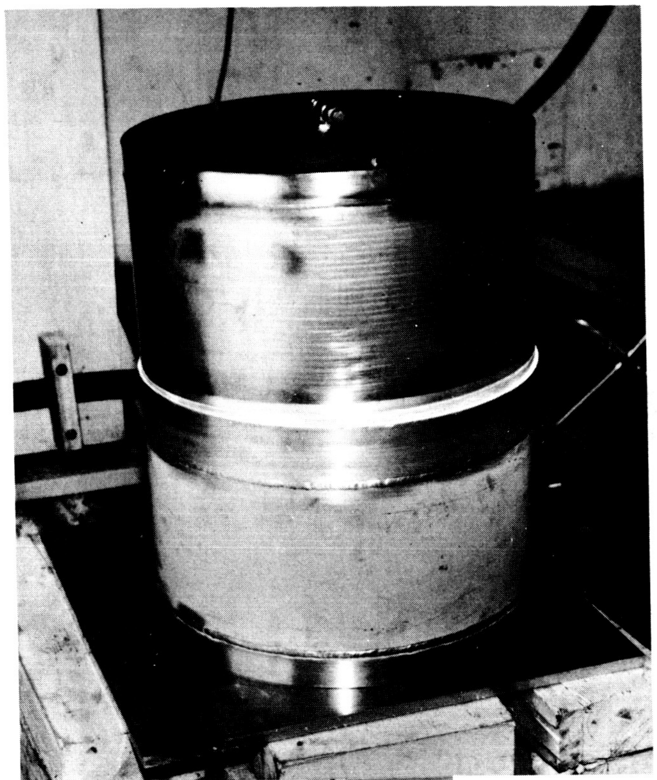
FIGURE

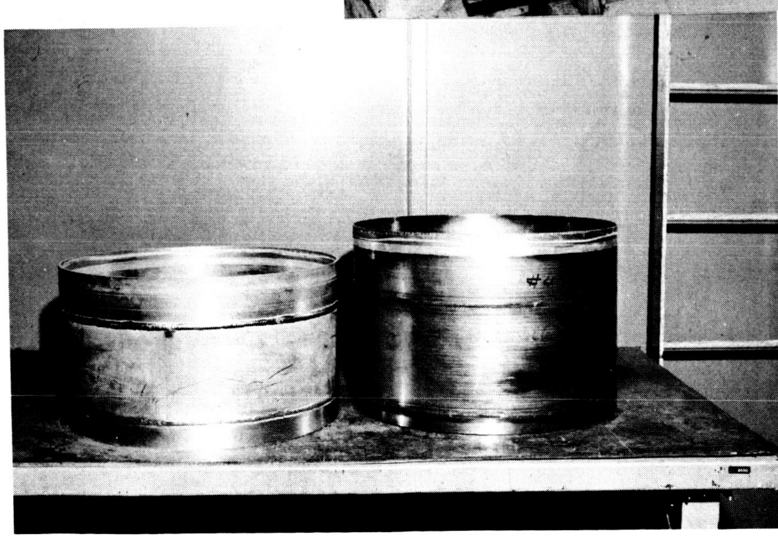
FIGURE 35: APPEARANCE OF DIFFUSION BONDED ASSEMBLY #4 AFTER REMOVAL OF MANDREL

No 1. Assembly

470 Psig Burst

RT





No. 4 Assembly

670 Psig Burst

$-320°$ F

FIGURE 36

APPEARANCE OF TANKS AFTER BURST TEST

APPENDIX A

JOINING OF DISSIMILAR METALS
A LITERATURE SURVEY

TABLE OF CONTENTS

ABSTRACT

A comprehensive literature survey has been conducted on methods for the joining of dissimilar alloys by welding, brazing, diffusion bonding and soldering. The survey was directed primarily toward processes which are used for joining aluminum alloys to stainless steels.

The brazing and welding processes required the stainless steel to be precoated by aluminizing or electroplating prior to joining to permit wetting by the brazing or welding filler alloy. Welding or brazing usually resulted in the development of a relatively brittle iron-aluminide phase in the interdiffusion zone. Aluminum is easily soldered to steel and copper alloys with the use of tin-lead or zinc base solders.

Diffusion bonding of dissimilar metals in the bare condition requires clean surfaces and high pressure and/or temperatures to produce a bond. The most successful method used a pressure which was high enough to deform the metals and cause plastic flow at the faying surface to break oxide films which are always present. Diffusion bonding is easily performed using surfaces which are electroplated with gold, copper or silver.

Dissimilar joints of steel and aluminum should not be solution heat treated after welding because of the formation of brittle intermediate phases at the joint faying surface. Corrosion of dissimilar metal joints may be minimized by the selection of metal combinations which have similar values for their electromotive solution potential.

INTRODUCTION

The survey of literature related to the joining of dissimilar metals revealed various investigators usually emphasized a particular problem or phase of a joining process.

To facilitate the analysis of the literature the most important facet of each investigator's work has been compiled in one or more of the following groups:

Precoating of Steel
Fusion Welding
Brazing and Soldering
Diffusion Bonding
Miscellaneous Joining Methods
Heat Treatment
Corrosion Resistance

PRECOATING OF STEEL

Aluminum and its alloys can be joined to stainless steel and ferrous alloys by welding, brazing, soldering and diffusion bonding. All of these methods normally require the ferrous alloy to be precoated in some manner to increase its wettability during the joining operation.

Miller[1] reports that the precoat treatments increase the wettability of the steel and also permit the joining operation to be performed at a short time at temperature, thus forming a lesser amount of the brittle intermediate phases. Miller reported the successful use of the following precoat treatments:

a) Coating the steel with tin solder or pure zinc prior to gas torch welding the steel to aluminum.

b) Electroplating steel with zinc, copper or nickel prior to brazing to aluminum.

c) Coating steel by hot dipping in molten aluminum prior to brazing of steel to aluminum. Miller notes that this process produces brittle iron-aluminide at the interface.

d) Coating both the steel and aluminum with a silver electroplate prior to diffusion bonding of the parts.

Miller and Mason[2] discussed two methods for precoating 304 stainless steel prior to welding the steel to aluminum. The steel was precoated by hot dipping in 1100 aluminum alloy for 20 seconds at 1275-1300°F, and by rub coating with 718 aluminum alloy. The interfacial iron-aluminide zone produced by the 718 alloy was thin in comparison to that produced by the 1100 alloy.

Finke and Begeman[3] discuss the quality of aluminized coatings produced by Armco Steel Corporation. The steel was coated by hot dipping in pure aluminum and by hot dipping in an aluminum alloy containing 8.5% silicon. The alloy containing silicon produced a thinner iron-aluminide diffusion zone than that produced by the pure aluminum.

Stevens[4] and Seal[5] reported on joining of steel to cast aluminum by the Al-Fin process. In this process the steel is precoated by dipping in molten aluminum. The iron-aluminide interfacial zone was normally .0004" thick and the process was controlled to prevent the zone from exceeding .001" in thickness. The micro-hardness of the iron-aluminide layer was measured as approximately 875 Vickers DPH.

Andrews[6] determined that steel which was precoated with molten tin produced good fillet shear strength when welded to aluminum alloys.

NUCO[7] developed a process for brazing stainless steel tubes to 6061 aluminum alloy. The steel was electroplated with a .0005" thick layer of tin prior to brazing.

Solar Aircraft[8] developed a process for brazing 3003 aluminum to 321 stainless steel. The steel was plated with titanium prior to brazing. Titanium reduced the amount of iron-aluminide which formed during the brazing process.

Stroup and Purdy[9] reported on all the known processes for applying an aluminum coating to steel. The processes discussed were primarily for use as a corrosion resistant coating. Of interest in their discussion is how the variables affect the formation of the iron-aluminide interfacial zone. The paper states that the iron-aluminide formation starts to form at 1100°F and its formation will increase as the time at temperature increases. The paper shows that aluminum-silicon alloys produce a thinner layer of iron-aluminide than that produced by pure aluminum for any given time and temperature.

Carson[10] reported on all known processes for protection of carbon steels from corrosion by the use of protective metal coatings. Hot dip aluminum gave good corrosion resistance. The interfacial iron-aluminide zone was kept thin as possible to permit bending of the aluminized steel during fabrication processes. Minimum bend radius for aluminized .040" thick steel was 3T. It is assumed that this refers to the minimum radius to prevent cracking on the aluminum outside surface and does not refer to the iron-aluminide interfacial zone.

Lamb and Wheeler[11] conducted an investigation to identify the composition of an aluminized coating produced by dipping steel into an aluminum bath containing 1.1% iron and 2.8% silicon. The analysis performed by electron-probe microanalysis showed that the aluminum coating consisted of three zones. The innermost (next to the steel) contained Fe_2Al_5; the middle zone contained $FeAl_3$, and the outer zone contained the as-dipped aluminum alloy dispersed with small particles of $FeAl_3$.

FUSION WELDING

Aluminum alloys can be welded to dissimilar alloys provided the dissimilar alloy is precoated with an alloy which will assist wetting and one which will retard the formation of brittle intermediate phases. During welding the dissimilar metal is generally not melted but only heated high enough to be wet by the aluminum alloy filler metal.

Orysh, Betz and Hussey[12] investigated methods for welding 2024 aluminum alloy to low carbon steel. The steel was used in three precoated conditions - (1) a zinc coating .001 inches thick applied by hot dipping, (2) an aluminum coating .0005" thick applied by hot dipping and (3) a silver braze alloy coating (either BAg-3 or BAg-10) .015 inches thick applied by an oxyacetylene torch. The aluminum was welded to the steel using the GTA process and with 718 aluminum filler alloy.

Shear and tensile specimens were prepared for static test and metallographic examination. The specimens tested using steel which was precoated with zinc or aluminum usually failed at the weld to steel interface due to the formation of iron-aluminide during welding. The specimens tested using steel which was precoated with the silver alloy usually failed at the weld to silver interface due to a new phase which formed between the silver and aluminum during welding. The shear strengths obtained by the three methods cannot be compared because fillet weld size is not clearly indicated in the report.

Stoehr and Collins[13] describe a method for GTA spot welding of steel to aluminum. The procedure used in making the GTA spot welds is similar to that for making aluminum to aluminum spot welds - the only difference being a pilot hole required in the steel when its thickness exceeds .030 inches. Aluminum alloys were used for the filler wire. When making the weld, some of the steel is melted; however, the arc force pushes the molten steel to the outside periphery of the weld and leaves a core of relatively pure and ductile aluminum filler metal.

The welds possessed adequate ultimate shear strength but developed a loose joint at partial loading due to fracturing of the brittle iron-aluminide. The "head" of the weld acts similar to a rivet head and prevents joint separation. Successful welds were made when joining various aluminum alloys to aluminized steel, bare steel and to galvanized steel. GTA spot welds for joining aluminum to steel are presently used on non-structural commercial applications.

Miller and Mason[2] discuss a procedure for GTA welding aluminized (hot dipped in 1100 alloy) 304 stainless steel to 6061 and 3004 aluminum alloys. The authors state the joints must be designed so the arc can be concentrated on the aluminum side of the joint to prevent overheating and cracking of the aluminized surface of the steel. Such cracks do not heal and are a source of weakness or leakage in the joint. Properly made welds are vacuum tight and will resist thermal shock. The average shear strength of welds made using 4043 aluminum alloy filler wire was 10,500 psi.

U. S. Patent 2,790,656[14] relates to a method for joining aluminum to steel and copper. The method was primarily developed where high joint conductivity and elevated strength were needed for joining electrical bus bars made from the above dissimilar metals. The joining is accomplished by first coating the steel or copper with a silver braze alloy followed by GTA welding the dissimilar metal to aluminum using an aluminum alloy filler wire.

U. S. Patent 2,239,018[15] relates to a flux which is used for welding aluminum to copper. The flux is composed of alkali metal halides and 20 per cent cadmium chloride. At welding temperatures the cadmium chloride decomposes and deposits metallic cadmium which increases wettability of the copper and permits welding using aluminum alloy filler wire.

BRAZING AND SOLDERING

Aluminum alloys can be dip or torch brazed to precoated steel or copper. The aluminum silicon alloys (1070°F melting point) are used as the brazing filler metal. The literature survey indicates that cylindrical parts up to 6 inches in diameter have been joined by this method. Soldering of aluminum to steel and copper is easily accomplished, using lead-tin solders, if both parts are pretinned prior to making the joint. Corrosion from the flux and dissimilar metal combinations is the major problem with soldered joints.

Miller[1] reports that aluminum may be directly soldered to steel and copper alloys if a zinc base solder and an active flux is used. Aluminum may be soft soldered to almost any alloy if the aluminum is pretinned with a zinc base solder and the dissimilar alloy is pretinned with a lead-tin solder. The parts are then cleaned and joined using a lead-tin and resin flux.

Miller[1] reports that aluminum alloys may be brazed to steel alloys by the torch or dip methods providing the steel is precoated. The best coating for steel is aluminum or aluminum alloys applied by hot dipping. Electroplatings of copper, nickel, iron or zinc on the steel promote wetting and have been used successfully.

Orysh, Betz and Hussey[12] tested brazed single lap shear specimens produced by two companies. The test results are as follows:

Company A

Three specimens of 0.125" 6061 aluminum were joined to .125" 1020 steel (.125 inch overlap) with 718 braze alloy and heat treated to 6061-T6 after brazing.

The average tensile-shear strength was 6500 psi.

Company B

Ten specimens of .125 inch 3003 aluminum alloy were brazed to .125 inch 347 stainless steel (.125-inch overlap).

The average tensile-shear strength was 9,600 psi.

The Bi-Braze Corporation[16] reported the results on testing performed on 1 and 2-inch diameter 304 stainless steel tubes dip brazed to 6061 aluminum alloy. The joints were thermally cycled 20 times from R.T. to -320°F without loss of strength or without leaking when inspected with a helium leak detector.

The Boeing Company[17] fatigue tested 304 stainless to 6061 aluminum alloy dip brazed joints. The steel tube wall was .032 inches and was brazed into a 6061 aluminum sleeve having a wall thickness of .090 inches. The joint overlap was .500 inches and 718 aluminum alloy was used for brazing. The specimens were tested to failure at -320°F. All failures occurred in the steel tube.

DIFFUSION BONDING

Aluminum alloys have been diffusion bonded to dissimilar metals using high pressures and at temperatures varying from RT to 1100°F. The diffusion bonding of aluminum to dissimilar metals at lower pressures and temperature requires the metals to be electroplated with a metal such as silver, gold, nickel or zinc. Diffusion bonding has been referred to by several terms such as pressure welding and cold welding. All processes which are related to diffusion methods are included in this section.

U. S. Patent 2,908,073[18] relates to methods for bonding aluminum alloys to steel and copper alloys. The methods outlined are adaptable for joining flat plates of aluminum to steel for use in the manufacture of electric flat irons and cooking utensils. Prior to joining, both the aluminum and the dissimilar alloy are cleaned by mechanical or chemical means. The parts being joined are pressed together to exclude air from the joint and are heated to a temperature range of 700 to 950°F. Pressure is increased to cause the aluminum to flow laterally. The pressure required varies from 15,000 to 50,000 psi depending on the temperature used. The aluminum thickness is reduced from 10 to 50% during bonding. The patent claims bonded joints can be obtained which have high peel strength and without the formation of intermediate phases.

Dulin[19] discusses various applications for the pressure bonding of aluminum to steel and copper alloys using the process described in the above patent. A number of examples are described of aluminum alloys bonded to stainless steel for fabrication, flat irons, cooking utensils and transition tubes.

Wood[20] in an article discusses fabrication methods which may be used on stainless steel clad aluminum (clad by the above process). The article states that the aluminum surface of the steel clad aluminum may be brazed to other aluminum alloys by torch or dip methods and that the steel surface may be arc welded to other steel alloys.

Cooke and Levy[21] investigated the diffusion bonding of various aluminum alloys to 18-8 stainless steel. Both metal combinations were in the bare condition. Diffusion bonding was accomplished by the following three methods:

1. By pressing a bar of aluminum to a bar of stainless steel (butt joint). At the desired pressure and temperature the bars were twisted in relation to each other to produce the bonded joint.

2. By inserting a tapered stainless steel rod into a tapered hole of an aluminum block and heating to the desired temperature followed by pressure to force the steel rod into the tapered hole to produce the bonded joint.

3. By pressing an aluminum alloy block against a stainless steel block (butt joint) at the desired temperature. Pressures approximating four times the yield strength were used. Both parts were enclosed in a die to prevent the aluminum from flowing.

The above tests were conducted at temperatures from 400 to 850°F. Tensile strength of the bonded joints varied from 10,000 to 30,000 psi.

All tests were conducted in air. Prior to bonding, the parts were cleaned by mechanical methods.

Koziarski[22,23] discusses applications where ultrasonic welding has been used to join 321 stainless steel to 6061 aluminum alloy. Single spot welds having high shear strength can be made without cracking of the base metal or development of brittle intermediate phases. Difficulty was encountered when a circumferential seam weld was made to join a 321 steel to a 6061 aluminum alloy flange. Both materials were .031 inches thick. The sonotrode force and vibration caused a cumulative flow of the alloys and resulted in welds that leaked and in base metal cracking.

Barta[24] investigated low temperature diffusion bonding of 2219, 6061 and 7075 aluminum alloys in the bare, and electroplated condition, and by using metal foils placed between the bare aluminum alloys. All diffusion bonding was accomplished by preloading the specimens and using an air atmosphere. All bonding was done using similar alloy combinations.

The 6061 and 2219 alloys were diffusion bonded at 450°F using high pressure but without yielding the base metal. The shear strengths were approximately 3500 psi. Silver plated specimens gave a shear strength of 6700 psi.

Young and Jones[25] discuss the joining of several alloy combinations by diffusion bonding in vacuum, using high temperature and pressures. Alloy combinations that were successfully bonded and produced ductile joints were columbium Cb-1Zr alloy to molybdenum Mo-1/2 Ti alloy, copper to columbium Cb-1Zr alloy, copper to 316 stainless steel and molybdenum Mo-1/2 Ti alloy to Rene' 41.

Neiman, Sopher and Rieppel[26] investigated the diffusion bonding of beryllium-copper to Monel. To retain the strength of the beryllium-copper, the bonding was accomplished below 1000°F. To accomplish solid state bonding at low temperature the authors decided that both the beryllium-copper and Monel should be electroplated prior to bonding.

The majority of the diffusion bonding was performed at 650°F (in inert atmosphere) which is the age hardening temperature of the beryllium copper (Cu-2Be) alloy. A bonding pressure of 6500 psi was found to be adequate.

In all tests two plating metals were used, one on the beryllium-copper and a different metal on the Monel. Good diffusion bonding was obtained using gold-copper and gold-silver plating combinations. These combinations gave shear strengths of 13,000 psi.

Parks[27] refers to solid state diffusion bonding as recrystallization welding. The author states that in order to establish a metallic bond the metals must be brought into intimate contact at a temperature which corresponds to or exceeds their recrystallization temperature. During recrystallization the thin surface film which exists on all metals is believed to coalesce and permit atomic registry between the metals during the formation of the new crystalline structure.

The article lists the recrystallization temperature for several metals and shows their recrystallization temperature decreases as their percentage of cold work increases. Silver has a recrystallization temperature varying from 230 to 482°F, aluminum (1100 alloy) from 510 to 685°F, iron from 770 to 968°F and nickel from 780 to 1157°F. The higher temperatures for each metal shown above is for approximately 10% cold work and the lower temperature is for approximately 90% cold work.

The bond shear strength of several alloys was determined by making single lap specimens in a manner similar to spot welding. The electrodes were heated with nichrome wire. Electrode pressure was not measured but was applied to a degree which would produce 5 to 10% indentation into the metal. The bond nugget diameter was approximately 0.150 inches. All test work reported was for the welding of similar alloys. The following table gives typical shear values for various bonding temperatures. The data indicates that bonding temperatures which exceed the crystallization temperature were required.

Metal	Temp. °F	Bonding Time Minutes	Shear Strength Psi
SAE 1020	730	2	No bond
	800	2	39,900
	900	2	38,900
1100 Aluminum	415	15	No bonding
	461	15	13,100
	517	15	10,200
Silver Clad Aluminum	205	1	No bonding
	280	1	8,700
	400	1	15,600
	470	1	22,400

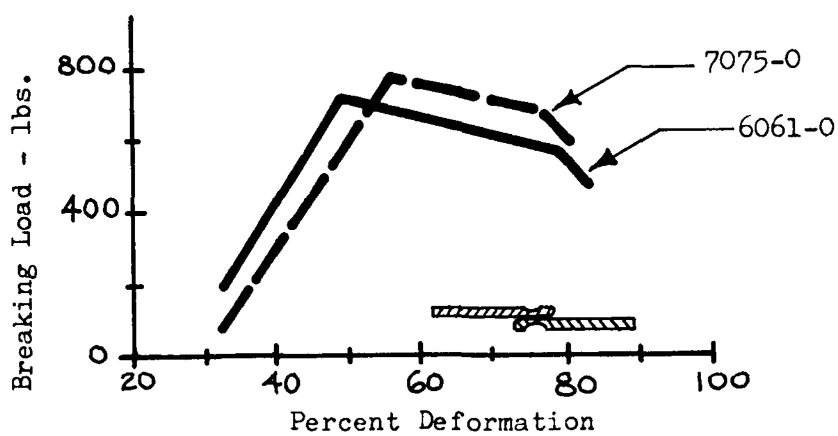
Prior to welding, the metals were cleaned chemically followed by some type of mechanical cleaning such as scraping or wire brushing. The surfaces must be free of oxide film and any contamination to produce good welds. The 1100 aluminum alloy lost half of its weld shear strength if welding was delayed 60 minutes after cleaning. This was attributed to the development of an oxide film during the 60 minute holding period.

Miller and Oyler[28] investigated the feasibility of solid phase pressure welding of 1100, 3003, 5052, 7075 and 6061 aluminum alloys. Various time and pressure cycles were used while varying the bonding temperatures from RT to 1100°F.

Successful solid phase welding could be accomplished at any temperature providing pressure was high enough to cause metal flow which would bring the metal into intimate contact and break surface oxide films. The best results were obtained when bonding temperatures were above 600°F.

Surface contamination was found to be extremely detrimental to the formation of a successful weld. Wire brushing was found to be the most satisfactory method for surface preparation. Etching the aluminum with 15% hydrofluoric acid was a satisfactory cleaning method when bonding at elevated temperatures.

The optimum material deformation for 6061 and 7075 aluminum alloy (caused by bonding pressure) was found to be approximately 50 per cent as determined by static testing of single lap joints. The following table shows the shear strengths for 6061 and 7075 aluminum alloys welded at room temperature.



Successful solid phase welding of aluminum alloys depends on temperature pressure and time. A decrease of any one of the variables requires an increase of one or both of the other variables.

A small effort was devoted to solid phase welding of aluminum to other metals. A successful lap joint was made between EC-O Aluminum and mild steel using a 5300 psi pressure, at 1170°F temperature and for a time of 7 minutes.

Butts and Van Duzee[29] studied the time-temperature-pressure relationships for pressure welding of silver. Also considerable effort was given to determine the effect of surface contamination on the bonding of the silver.

The authors stated that no firm bond was obtained below the recrystallization temperature (199°C) of the silver. Solid state diffusion bonds were obtained in less than one hour when a temperature of 400°C and bonding pressure of 30,000 psi was used.

Thin films of foreign matter were introduced between silver strips to determine their effect on the welding. Substances used for contaminating the surface were copper oxide, iron oxide, silver oxide, aluminum oxide, silver sulfide, charcoal, mineral oil, talc and lubricating grease. None of the films materially reduced the bonding of the joint. The authors believe that the high bonding pressure destroys the continuity of the film and permits it to coalesce into particles. The resultant finite particle area is not great enough to cause an appreciable loss in strength.

Orysh, Betz and Hussey[12] investigated procedures for diffusion bonding 3003 aluminum alloy to 304 stainless steel and 2024 aluminum alloy to 1020 steel. In all cases the steel was precoated with a silver brazing alloy (BAg-10) using an oxyacetylene torch. The silver layer was then ground flat to a thickness of .005 inches.

Prior to bonding, the silver layer was cleaned with alcohol and the aluminum was chemically cleaned using an alkaline etch followed by dilute nitric acid and water rinse. Bonding was attempted at temperatures varying from 200°F to 800°F using pressure for a time of two minutes. From this screening test the authors selected a bonding temperature of 800°F and a pressure of 2400 psi (2.3% joint deformation) as being optimum.

The following table shows the shear test results for silver coated 1020 steel bonded to 2024 aluminum alloy.

RESULTS OF SINGLE LAP SHEAR TEST

Pressure psi	Temp. °F	Time Min.	Shear Strength* psi
2400	800	10	2070
2400	800	30	1900
2400	800	60	2730
2400	800	120	3330
2400	800	180	3110
2400	800	240	2300

*Average of three specimens

Metallographic inspection revealed that diffusion had not occurred uniformly across the joint interface.

Hess and Nippes[30] investigated the joining of aluminum to steel by resistance welding. The application was for joining aluminum cooling fins to SAE 4140 steel aircraft engine cylinders. The authors determined that the resistance welding had to be accomplished without melting of the steel because of the formation of brittle iron-aluminide phases at the interface. It was also necessary to create a weld (or bond) without heating the steel above its austenizing temperature to prevent a martensitic structure from forming during cooling of the weld (or bond).

Although aluminum (3003 alloy) could be resistance bonded to a SAE 4140 without overheating of the steel, the welds always failed in a brittle manner because of the iron-aluminide which formed at the interface. From this the authors determined that a third metal (located between the steel and aluminum) was necessary to prevent the direct contact of the steel and aluminum. Because of the difficulty of using metal foils all test work was done by welding bare (cleaned) aluminum to electroplated steel.

The metals used for plating were tin, zinc, silver, copper, nickel, chromium and cadmium. The authors recognized that all of the above alloys could form intermediate phases with either the aluminum or with the steel if the temperature and alloy concentration were of an unfavorable magnitude during the resistance heating cycle.

Bare (cleaned) aluminum was resistance bonded to bare and plated steel using 800 pound electrode force and 10 cycles welding time. Current was varied to produce the desired penetration into the aluminum side of the joint. A plating thickness of 1/4 to 1/2 mil was found to be adequate for bonding. The following table gives typical shear strength of test selected from data presented. Failures were classified as (1) ductile tear (DT) when a nugget was pulled from the aluminum, (2) ductile shear (DS) when the bond failed at the interface after considerable bending of the aluminum had taken place and (3) brittle shear (BS) when the bond failed at the interface without any bending of the aluminum sheet.

Cleaning requirements and plating procedures used on the steel are outlined in detail in the article. The authors state that plating procedures must be rigidly controlled because much of the bond strength of the joint depends upon the adherence of the plating to the steel.

Silver was selected as the most desirable metal for plating prior to resistance joining of the aluminum to steel. Copper was considered satisfactory but required more rigid welding controls to prevent brittle welds.

Welding Current (amps)	Plating Metal	Thickness Inches	Penetration %	Spot Shear Lb.	Failure Mode
15,700	None	- -	40	310	BS
16,100	None	- -	60	440	BS
16,600	None		75	470	BS
16,600	Tin	.00025	60	220	BS
16,400	Tin	.00050	30	170	BS
17,200	Tin	.00050	95	490	BS
18,000	Zinc	.00025	30	320	BS
18,600	Zinc	.0005	50	390	BS
19,300	Zinc	.0005	80	430	BS
17,800	Silver	.00025	60	530	DT
18,400	Silver	.0005	50	570	DT
19,800	Silver	.0005	60	590	DT
19,200	Copper	.00025	30	420	BS
20,600	Copper	.00025	50	530	DS
21,400	Copper	.0005	20	450	BS
24,800	Copper	.0005	50	570	DT
15,100	Nickel	.00025	70	440	BS
15,400	Nickel	.00025	80	490	DS
15,000	Nickel	.0005	50	150	BS
15,700	Nickel	.0005	90	480	DS
19,400	Chromium	.00025	70	460	BS
20,600	Chromium	.00025	80	470	DS
18,400	Chromium	.00050	35	430	BS
19,000	Chromium	.00050	40	470	DS
16,000	Cadmium	.00025	50	400	BS
16,400	Cadmium	.00025	80	480	DS
16,200	Cadmium	.0005	50	420	BS
16,600	Cadmium	.0005	60	470	DS

Finke and Begeman[3] and boecker and Begeman[31] developed resistance welding procedures for seam welding aluminum clad steel. Two types of aluminized coatings were evaluated; type 1 was an aluminum alloy containing 8.5%

silicon and type 2 was commercially pure aluminum. Welding schedules were developed which varied from zero penetration to 75% penetration into the steel base metal. The welds without penetration produced a bond by brazing the aluminized surfaces together. When the weld penetrated into the steel the aluminum coatings were squeezed from the joint, giving a steel-to-steel weld.

Overlapping of the weld nuggets was difficult to obtain using the Type 1 coating, and easily obtained when using the Type 2 coating. However, lack of nugget overlap did not necessarily mean the joints were not leak tight because of the brazing action that took place between the aluminum coatings. Nugget voids, inclusion and cracks were commonly observed; however, when testing the weldments with a pillow test, the failure always occurred in the steel base metal adjacent to the weld.

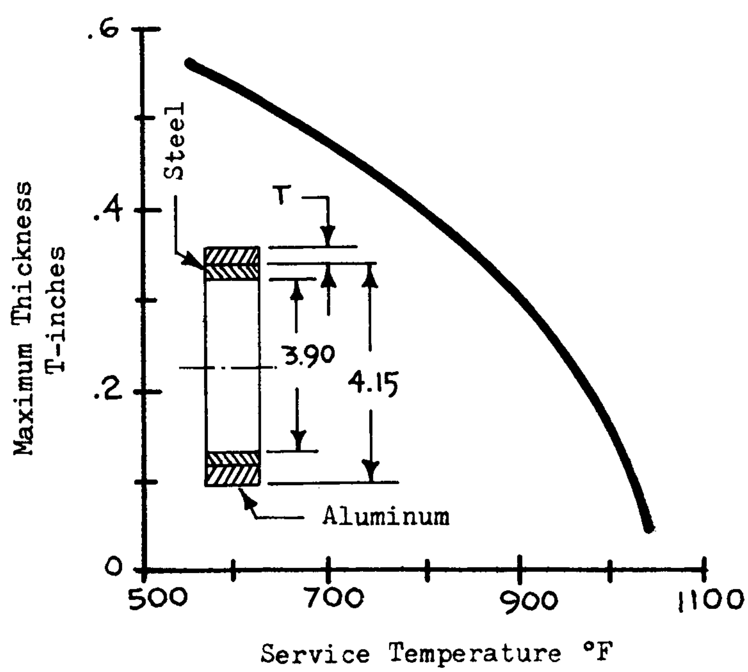
MISCELLANEOUS METHODS

Zimmer[32] discusses a new technique for joining two metals (called Component A and Component B) which vary considerably in their chemistry and/or coefficient of thermal expansion. The article proposes that a third member (called a coupling) be manufactured and inserted between the two dissimilar metals. The coupling would be made by powder metallurgy and its composition would vary from end to end so that End A would be compatible with Component A and End B would be compatible with Component B. Joining of the coupling to the dissimilar metals would then be performed by welding or brazing.

Stevens[4] discusses the procedures used in joining steel to aluminum by casting the aluminum around the steel using the Al-Fin process.

Joints tested by the author were found to be pressure tight when tested at 1000 psi using nitrogen gas. Socket type joints made of steel to cast aluminum develop shear strength varying from 11,000 to 17,500 psi. Shear tests conducted 500°F show no reduction in strength.

Seal[5] in an article which describes the Al-Fin process in detail includes data on the thermal coefficient of expansion of various steel and cast aluminum alloys which are currently being joined by this process. Of particular interest and value is the following curve which shows the maximum thickness an outer aluminum cast shell, can be to prevent bond separation when the part is subjected to elevated temperatures.



HEAT TREATMENT

Aluminum alloys which have been joined to a dissimilar alloy may be resolution heat treated. However, most investigators have found that exposure to elevated temperature will cause a decrease in joint strength because of a formation of brittle intermediate phases at the joint interface. Resolution heat treated parts are air cooled to prevent joint failure from thermal shock.

Cooke and Levy[21] showed that the aluminum to steel joints diffusion bonded (discussed on page 10) had an increase in strength if the parts were annealed after bonding. Parts which, when resolution heat treated (air cooled) and aged also developed more strength if the solution heat treat temperature was below 930°F. Temperatures above 930°F caused a high increase in diffusion rates and produced a thick layer of iron-aluminide at the joint interface and reduced the tensile strength of the joint.

Miller and Mason[2] presented data showing how the shear strength of welds on stainless steel to aluminum joints deteriorated upon exposure to elevated temperature. Exposure at 700°F for 5 hours reduced the shear strength 50 per cent and exposure to 900°F for 30 minutes reduced the shear strength 40 per cent. Tylecote[33] showed the strength of pressure welds between aluminum and steel (both in the bare condition) exposed at 900°F for 30 minutes decreased from 375 pounds to a 150 pound failing load. The authors believed that diffusion at these temperatures caused an increase in thickness of the iron-aluminide interfacial zone.

CORROSION RESISTANCE

Corrosion of a dissimilar metal joint is inevitable if there is an electrolyte present. The degree of corrosion which takes place is dependent upon the type of electrolyte and the difference of the electromotive potential between the dissimilar alloys.

Young and Smith[34] discuss the problem of galvanic corrosion between dissimilar metals. Solution potentials of several metals and intermediate compounds are listed below. The magnitude of their effect depends on the nature of the electrolyte and difference in potential between the alloys being joined. The anode (material with highest potential) will be consumed by the electrolyte.

Decinormal Calomel Scale

Magnesium	1730
Zinc	1050
Aluminum Alloys	810-850
Mild Steel	780
Tin Plate	740
Iron	580
$FeAl_3$	560
$CuAl_2$	530
Silicon	260
Copper	220
Stainless Steel	130-430
Nickel	140
Silver	80

Singleton[35] and Dowd[36] discuss the use of high melting solders for joining aluminum alloys. The solders which produce the highest corrosion resistance for aluminum are the pure zinc (787°F melting point) or zinc containing small amounts of aluminum or magnesium. Dowd gives the following electrode potentials for several metals for a 1N NaCl + .3% H_2O_2 solution when using a Decinormal Calomel reference electrode.

Electrode Potentials

Zinc	-1.10
Aluminum	- .83
Iron	- .63
Tin	- .49
Copper	- .20
Silver	- .08
Nickel	- .07

Doss[37] investigated methods for coating trimetal assemblies made up of steel, aluminum and magnesium. The best coating was found to be tin which was applied by dipping the trimetal assembly in a neutral (pH7) stannous pyrophosphate plating solution. All three metals were plated with tin without chemical attack to the base metals. The tin coated assemblies showed good resistance to galvanic corrosion when tested in a salt fog environment.

Stoehr and Collins[13] subjected GTA spot welded steel to aluminum specimens as described on page 6 to 3-1/2% NaCl spray test for 42 days. The aluminum to aluminized steel specimen showed minor surface pitting. The welds on aluminum to bare and to galvanized steel permitted corrosion along the aluminum to steel interface.

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APPENDIX B

PROCEDURE FOR PLATING 321 STAINLESS STEEL

1. Vapor degrease.
2. Cathodic clean in alkaline electrocleaner.
3. Anodic electroetch in 60% H_2SO_4 - 45 Sec.
4. Strike in all chloride nickel strike - 30 Sec.
5. Silver plate in Lea-Ronal proprietary silver plating solution - .0005 inch thick.

(Tap water rinse after steps 2 through 6)

PROCEDURE FOR PLATING 2219 ALUMINUM ALLOY

1. Vapor degrease.
2. Soak clean in non-silicated aluminum cleaner.
3. Deoxidize at room temperature.
4. Dip in nitric-hydrofluoric acid - 5 seconds.
5. Zincate (conventional zinc immersion bath for aluminum).
6. Remove zinc by dipping in concentrated nitric acid.
7. Repeat step 5.
8. Copper strike in conventional Rochelle salt copper cyanide plating solution with 10.0-10.5 pH. Thickness of copper .00002 to .000025 inch.
9. Silver plate in Lea-Ronal proprietary silver plating solution - .001 inch thick.

(Tap water rinse after steps 2 through 9)

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APPENDIX C

PROCEDURE FOR PLATING 321 STAINLESS STEEL

1. Vapor degrease.
2. Cathodic clean in alkaline electrocleaner.
3. Anodic electroetch in 60% H_2SO_4 - 45 Sec.
4. Strike in all chloride nickel strike - 30 Sec.
5. Copper plate in conventional Rochelle salt copper cyanide plating solution - .0005 inch thick.
6. Silver plate in Lea-Ronal proprietary silver plating solution - .0005 inch thick.

(Tap water rinse after steps 2 through 6)

PROCEDURE FOR PLATING 2219 ALUMINUM ALLOY

1. Vapor degrease.
2. Soak clean in non-silicated aluminum cleaner.
3. Deoxidize at room temperature.
4. Dip in nitric-hydrofluoric acid - 5 seconds.
5. Zincate (conventional zinc immersion bath for aluminum).
6. Remove zinc by dipping in concentrated nitric acid.
7. Repeat step 5.
8. Copper strike in conventional Rochelle salt copper cyanide plating solution with 10.0-10.5 pH. Thickness of copper .00002 to .000025 inch.
9. Silver plate in Lea-Ronal proprietary silver plating solution - .001 inch thick.

(Tap water rinse after steps 2 through 9)